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PROGRESS IN RELIABILITY OF MILITARY ELECTRONIC EQUIPMENT DURING 1956

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Most engineers in defense who are engaged in various phases of developing, producing, maintaining and operating electronic equipment recognize the acute need for an extremely high level of reliability in the progressively more complex electronic portions of weapons and weapons systems. Even more significantly, this need is now appreciated generally throughout the industry engaged in developing and manufacturing military equipment. Although this increasing emphasis on reliability is important, even more gratifying is the realization that we are now making progress in actually improving the reliability of military electronic devices. No longer do we merely talk about the need for better reliability and what makes equipment unreliable; electronic equipments and systems of much improved reliability are now beginning to be available to the military services. This change from philosophy to action became apparent to me over this past year as I visited many companies in the electronics and aircraft industries engaged in the development and production of military equipments and weapons systems. Emphasis upon reliability in design and manufacture has increased greatly in only one year.

This encouraging trend is clearly indicated in the numerous fine papers presented in this study. Many discuss what has been done and is being done to obtain improved reliability. Previously the emphasis was more on what needed to be done and how it could be done. We haven't made reliability a definitely established science yet, but we are starting to give it equal consideration with other performance requirements in development and production.

As I stated in October, 1955, in an address at a reliability conference at Aberdeen Proving Ground, we have come to a point where the productivity of the general educational type of approach to reliability is diminishing. We now need to become more specific in our actions if we are to obtain the degree of reliability improvement demanded for military electronic equipment. I do not wish to infer that we should discontinue reliability education. It is essential that everyone connected with the job of developing, designing, producing, testing, installing, operating and maintaining military electronics be kept fully aware of the importance of reliability. We now know enough about some of the basic causes of unreliability to permit specific unified action to be taken in certain areas by the military departments. We are also sufficiently aware of the effects of unreliability to know that more drastic measures are justified.

Substantial progress has been made in reliability improvement during the past year as a result of hard work by many people in industry, in the three military departments and in various agencies of the Office of the Secretary of Defense. A few specific instances will illustrate where careful attention to reliability in equipment design has paid large dividends and has given excellent proof that really good reliability can be obtained on complex equipment through the proper application of existing components.

One of these equipments is an airborne digital computer designed to perform the bombing-navigation function. This computer contains approximately 10,000

electronic parts, including about 300 electron tubes, 5,000 crystal diodes and 96 transistors. The prototype of this computer has operated approximately 450 hours, including 135 hours in the air in actual bombing exercises. During this time there were four failures, only one of which affected flight availability. Another example is a transistorized multiplex telegraph terminal set containing 570 transistors and 739 diodes. The developmental model of this equipment has operated under typical service conditions for over 5,000 hours with only two transistor failures. There were no other failures.

It should be pointed out that in both cases only one equipment was tested, so the information is not conclusive. However, compared to equipments of older design in the same status, these indications of reliability improvement are indeed reassuring. There are also indications that in 1956 excellent progress was made in improving equipment reliability through the statistical analysis of equipments already in production and the correction of design deficiencies while the equipment was in the production line.

An outstanding example of this is an airborne navigation equipment developed for the Navy. For a year this equipment had been in limited production by three contractors. Although service requirements for the equipment were substantial, quantity production was held up because of indications of unsatisfactory reliability in service tests. The equipment had been in service evaluation by two military agencies for over a year. During this period only 5,000 set-operating hours were obtained, and correlation of flight data indicated the existence of nine design problems.

The cognizant military agency, realizing that flight testing was not providing enough data to obtain a good statistical measure of reliability, set up controlled tests in the laboratory in which 50 equipments were operated simultaneously under simulated operating conditions. In a period of four months, these simulated tests gave 50,000 set-operating hours on 150 different equipments, and the need for 22 design changes was indicated on the basis of correlated failure data.

These carefully designed tests showed that the reliability of this equipment had been improved by making the nine design changes found to be desirable during service evaluation tests and by introducing improved production controls, thus increasing the mean time to failure from 45 hours to 120 hours. Correction of the 22 design deficiencies discovered through the simulated tests should result in still further improvement in the equipment's reliability.

This program taught a major lesson regarding the value of simulated operating tests (where variables can be carefully controlled) in determining design and component weaknesses in a short period of time. Much time, money and manpower could have been saved in getting this navigation system into general service use if this kind of test had been made at the beginning of the program rather than in actual service flight.

In addition to establishing the value of statistically controlled simulated tests to rapidly determine design weaknesses and poor components, the Navy has included a firm requirement for reliability in its contractual specifications for procurement of large quantities of the equipment. This reliability specification is expressed in terms of mean time to failure, measured under specified test con-

ditions and procedures. To my knowledge, this is the first time reliability has been definitely specified in a procurement document, and it represents a great step forward in the campaign for better reliability.

Another example of reliability improvement through rapid feedback of failure data from the production line to the engineering department is in connection with a complex airborne fire-control system now in quantity production for the Air Force. Over the past year the mean time to failure of this system, based on production testing in the factory, has been increased from 3 hours to 18 hours. This substantial improvement was obtained by a careful and rapid correlation of problems occurring in the factory and the immediate analysis and correction of design deficiencies and weak component parts. This kind of in-production reliability improvement program can be really successful only if design and initial production are done by the same contractor.

These gratifying examples of improved reliability, obtained through better design and cooperative effort between production and engineering, are only a few of those which have recently come to my attention. But they are illustrative of the general trend throughout industry and the military departments to put far more emphasis on reliability than in the past. The excellent results demonstrated in these cases give support to the conviction that the right time to obtain reliability is during the development of the design and in the early stages of production where design deficiencies affecting reliability and producibility can be corrected before the item is quantity-produced for service use.

On July 5, 1956, the Secretary of Defense issued DOD Directive No. 3222.1 covering the approval of new electronic equipment and systems for service use. This directive makes it mandatory that the design of newly developed electronic items be adequately tested for reliability as well as for operational performance before production for service use is authorized. It also requires that new electronic equipments and systems be produced in pilot quantities and that they be further tested for conformance to reliability requirements prior to production for service use.

This directive, which has been formally implemented by the Department of the Army and is in the process of implementation by the Navy and Air Force, represents a major step forward in reliability. In my talk at Aberdeen I pointed out that the greatest cause of the present unacceptable level of reliability in military electronic equipment is the lack of maturity of product design and failure to evaluate the inherent reliability of design, through realistic engineering tests and service and materiel evaluation, before major production is undertaken.

Compliance with DOD Directive 3222.1 will greatly reduce the number of new equipments reaching the using services in a condition of unknown and unsatisfactory reliability. This will unquestionably ease the burden on the maintenance man and reduce the number of in-service field changes required. To carry out the intent of this new directive properly, it is essential that the development of the design and initial pilot production be done by the same contractor. This is the only realistic way to achieve the important teamwork between engineering and production needed to find and remove those reliability deficiencies which require the statistical data obtainable only through exhaustive testing of production models.

On February 23, 1956, the Assistant Secretary of Defense (Engineering) issued an instruction that will also contribute substantially to improved reliability in the near future. DOD Instruction No. 3232.2 establishes an improved electronic equipment failure data reporting system. The chief objective of this new system is to provide a uniform reporting system for all electronic equipment for every military department.

When fully implemented, this new reporting system will make available, on a more timely basis, much better information on reliability performance of equipment in service. The nature of the reporting forms are such that the information can be readily correlated and analyzed on computing machines. It is hoped that in future new equipments reaching the user most of the reliability problems will have been solved, but in order to determine the degree of correlation between reliability measurements made in the laboratory and factory and actual performance in the field, information from the using services is essential. These failure reports, when analyzed in large numbers on a broad base of equipments, will be extremely valuable in determining the index of reliability of specific tubes and component parts. It will provide excellent background information for the designer and manufacturer of both end-item equipments and parts.

The reliability requirement of the Department of the Navy is specified concisely in terms of average time to failure, and the tests to determine this reliability level are specified in detail. The contract requires that the manufacturer demonstrate the attainment of the specified level of reliability on production-line equipments before the government will accept it. Three contractors have accepted this reliability clause. Compared to the tremendous expense of maintaining unreliable equipment in service, it will be a good investment for the taxpayer despite an increase of cost to the government.

The Air Force has taken important action in the reliability improvement program during the past year, including the establishment of the Communications-Electronics Reliability Committee in July, 1956. The purpose of this committee (which is formed within Headquarters, Air Materiel Command, Wright-Patterson Air Force Base) is the surveillance of reliability for all electronic equipment developed and procured under the direction of AMC. Perhaps the objectives of this group can best be expressed by one paragraph from the Headquarters Office Instruction which established it:

> "Required Action. Committee members will keep abreast of the latest concepts of reliability and insure the timely integration of all aspects of reliability within communications-electronics equipment as designed, procured, manufactured, inspected, packaged, transported, supplied and maintained within the functional responsibilities of AMC."

Membership on this committee includes men from the directorates at AMC responsible for maintenance engineering, procurement and production, quality control, plans and programs, transportation and services and supply. The various activities within the Air Research and Development Command are also represented. This organization should provide excellent monitoring and coordination of reliability functions for all Air Force airborne electronic equipment.

Also in 1956 the Air Force initiated a specific program to establish definitive reliability specifications for a new airborne communications equipment, to

be presented so as to be applicable to other airborne communication and navigation equipments. The reliability aims of this program will be combined with the objective of establishing a basic modular design applicable to many types of airborne equipment. The modular design objective has also been pursued vigorously by the Navy, and a preliminary Bureau of Aeronautics specification has been issued and circulated. It is hoped that these Navy and Air Force efforts to develop a modular design philosophy can eventually result in a uniform design approach for all applicable airborne electronic equipment used by the three military departments. This would have a very beneficial effect on reliability because of the potential increase in production quantities of similar modules.

During the past year, considerable progress has been made by the military departments and by industry in improving the quality and reliability of electron tubes and component parts. The Army Signal Corps has continued its program to add to knowledge of the life characteristics of electron tubes and component parts, and failure rate has been included as a requirement in some specifications for new parts. Electron tubes for guided missiles, now becoming available, promise substantial improvements in reliability over those previously available. This advance in tube reliability is primarily the result of minor tube redesigns and much more careful control of environments and processes in manufacture.

In the area of microwave power tubes, there are indications that major reliability improvements have been made. ARINC, in a recent classified report on magnetron reliability, states: "One magnetron manufacturer was able to increase mean time to failure of a magnetron type in field service from approximately 45 hours to something over 500 hours through improved design and improved processing during manufacture. This improvement in mean life came about without equipment modification." This is certainly a sign of progress, since magnetrons have historically been a major source of unreliability and excessive maintenance cost in radar equipments. There are many other areas where the military departments and industry have come to grips with the reliability problem and found specific solutions, but they are too numerous to discuss in this paper.

In conclusion I would like to discuss the status of the Advisory Group on Reliability of Electronic Equipment. The function of this group is to advise the Assistant Secretary of Defense (Engineering) on matters pertaining to the reliability of electronic equipment and to maintain and stimulate interest in the subject of reliability and its improvement.

In the fall of 1955 AGREE embarked on an extensive program to attack the reliability problem in many specific areas. To assist them in this effort nine task groups were established, consisting of qualified individuals from industry, the military departments and various agencies of the Office of the Secretary of Defense. Each task group was assigned a specific problem to solve. The work -- which has been publicized a great deal over the past year -- covers the various phases of the life of a military electronic equipment from requirements through design, development, procurement, production, shipment and storage to operation and maintenance.

The nine task groups, consisting of a total working force of 37 people from industry and 96 from various parts of the Military, started work in February, 1956, on a schedule which at that time called for completion of the work in six months, if possible. The magnitude of the tasks, however, was greater than any

of us appreciated so the completion date was extended. The final reports from all of the task groups were finished and reviewed by the Advisory Group in January, 1957.

Almost without exception, the groups accomplished their assigned tasks. It is my opinion that their reports, when compiled and summarized, will represent the most complete and valuable analysis of the major phases of a reliability program ever compiled. They also include specific actions required to obtain reliable equipment. From this work should come the basis for quantitative reliability specifications, design procedures to be followed for reliable equipment, tests to measure reliability in the laboratory and the factory during development, pilot production and quantity production, recommendations relative to procurement practices, recommendations for solving some of the component problems, recommendations concerning packaging and shipment and suggestions as to how some of the pressing operating and maintenance problems can be solved.

The job of reviewing the reports of the task groups and implementing the recommendations is a formidable one. None of the individual reports will be published prior to completion of the over-all compilation of recommendations. The results of the total study will probably be available to industry this summer.

In reviewing the progress made during 1956 in electronic equipment reliability improvement, several very significant factors emerge. To summarize, here are some of the more important ones:

1. A fairly universal acceptance of mean time to failure as a means of expressing reliability has developed.

2. Policy has been established requiring that the design of a newly developed military electronic item be completed and thoroughly tested for reliability and producibility, as well as performance, before production for service use is started.

3. Equipment designers, who have become far more concerned about reliability, are applying more effort to obtain it. Some of the newly designed equipments tested recently have demonstrated an inherent reliability slightly greater than equipments now in service.

4. A definitive requirement for reliability, expressed in mean time to failure, has been included in a contract specification for the procurement of large quantities of a military electronic equipment.

5. The application of transistors to military equipments has started to expand.

6. The value of pilot production and reliability testing during the initial production period has been demonstrated.

7. The use of printed wiring has become more universal throughout military equipments, a potentially significant step forward in reliability.

8. Specific and substantial advances have been made in obtaining more reliable electron tubes and component parts.

9. Management throughout industry has developed a far greater understanding of reliability and what is required to obtain and maintain it.

We have certainly made excellent progress in reliability during the past year, but the job is only begun. We still face the very challenging problem of bringing reliability of electronic devices to a level that will be really acceptable for future applications. Weapons and weapons systems are becoming continuously more complex and the demand for better reliability increases accordingly. Missile systems, as well as aircraft, are becoming increasingly more costly and lethal. The penalty for weapon failure because of an electronic disturbance is becoming progressively more serious.

During the past few years, there has been a growth in understanding of what must be done in the various technical areas of components, equipment design, testing and manufacture to produce a reliable electronic equipment, and we have applied this knowledge successfully in many programs. However, comparable progress has not been made in improving the policies and practices of procurement.

Emphasis on competitive cost in the procurement of both development and production is still a major deterrent to obtaining real reliability in military electronic equipment. It is improbable that a highly reliable equipment will ever be produced if the price has been forced so low that shortcuts in engineering or manufacture are required. Nor have we made much progress in convincing procurement people that substantial reliability improvements result from keeping the same contractor on the job through development and initial production. It is hoped that 1957 will see these and other remaining obstacles overcome by direct action or further education.

The AGREE study should be completed and its major recommendations in effect before the end of the year. In particular, there should be a vast improvement in the over-all military management of component part activities, including the establishment of requirements and the preparation and approval of specifications and qualification for military use. From these will come further general improvements in quality and reliability of electron tubes and component parts. We need additional emphasis on the military application of semiconductor devices as a reliability improvement measure. A more widespread application of printed wiring and design for automatic assembly of military electronic equipment would contribute to reliability as well as enhance our mobilization potential.

THE MILITARY RELIABLE TUBE PROGRAM

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This paper reviews some of the more significant aspects of the tube reliability efforts being carried on by the military departments. From my experiences I must conclude that the term tube reliability is not an expression of inherent tube quality but rather has meaning only when related to particular applications of tubes.

THE PRESENT SITUATION

Operational Reliability

The military departments for several years have employed the services of Aeronautical Radio Incorporated to obtain from military operating bases field data on electronic tube and equipment reliability. These data cover most of the electronic equipments and associated weapons systems used by the military. Some recent data obtained by Aeronautical Radio from controlled observations aboard a Navy aircraft carrier have special significance. In the case of one equipment, the AN/SPA-8A radar plan position indicator, they represent the most reliable tube performance yet observed in military operations apart from fixed ground installations.

The survival pattern of the tubes that were under observation in this particular test is shown in Fig. 1. The AN/SPA-8A indicator is a moderately com-

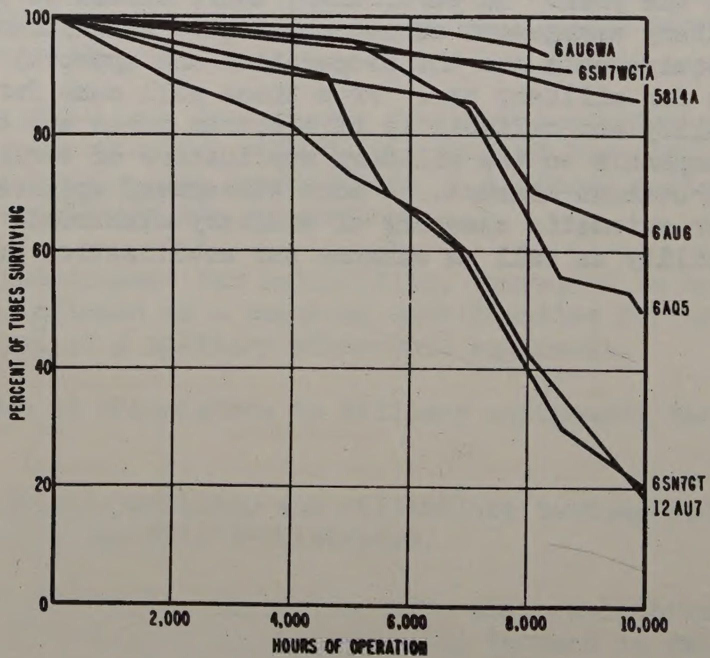

Fig. 1 - Survival pattern for control test tubes in AN/SPA-8A radar indicator.

plex equipment having about 135 tubes of the receiving class. The equipment is located in an environment rather ideal for tubes, having no severe temperature or acceleration conditions. The 14 indicators from which the tube data were taken were divided into two groups. While the first group was operated in the normal manner, the second was operated with low-pressure cool air supplied internally through an opening at the base of the indicator pedestal. The cool air reduced the tube envelope temperatures by about 30°C. The curves were plotted from data obtained and combined from both groups of indicators. In accordance with a predetermined installation plan, the tubes from which these data were taken were randomized as to socket location.

After 8,000 hours of service, tube type 6AU6WA had about 95 per cent of the tube surviving, as shown in Fig. 1. Conversely, the commercial prototype of this tube, 6AU6, had about 71 per cent of the tubes surviving at the 8,000 hour point. Similar comparisons can be drawn between reliable tube type 5814A and its commercial prototype, 12AU7. At the 10,000 hour point, these types had about 86 per cent and 18 per cent, respectively, surviving. Reliable type 6SN7WGTA presents an interesting comparison with its commercial prototype, the 6SN7GT. At the 8,000 hour point they have, respectively, about 92 per cent and 40 per cent surviving. Up to the time of the last observation from which these data were obtained, there were no failures of the reliable tubes beyond the accumulated hours shown in the figure. The ordinate for this curve really should be called "Probability of Survival" rather than "Per Cent of Tubes Surviving," since our

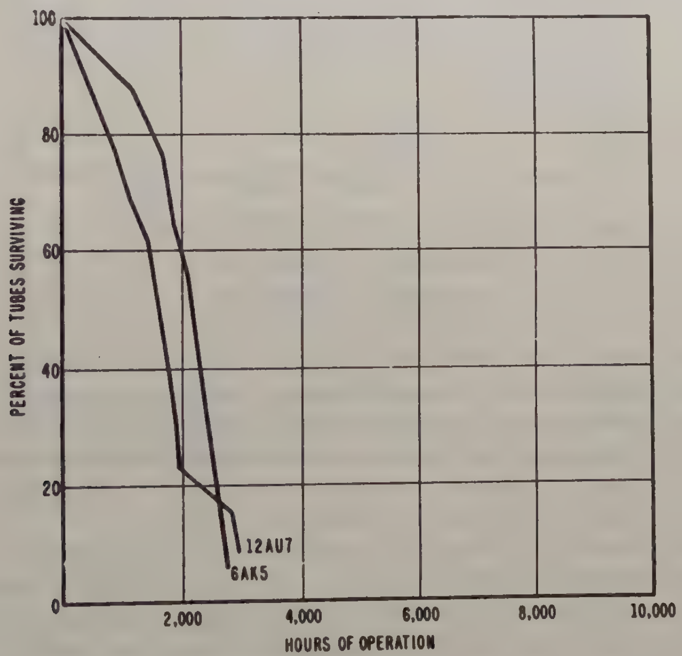

Fig. 2 - Survival pattern for control test tubes in AN/URT - 2, 3 & 4 radio transmitters.

plots are from computed values that consider the reduction in the size of our test sample as defective tubes are removed.

A receiving tube survival pattern not quite as good as the previous pattern is shown in Fig. 2. The data for this figure were obtained from the AN/URT-2,3-4

series of radio transmitters. These are high-frequency transmitters, each type having about 125 receiving type tubes in its complement. In this test there were comparisons made between the tube types shown in the figure and their reliable counterparts. The survival pattern for the reliable counterpart tubes does not differ appreciably from those shown in the figure. There appear to be present certain detrimental factors that play no favorites with tube types. While Fig. 2 presents an unfavorable picture when compared with the previous figure, nevertheless it is much more representative of tube survival patterns in military electronic equipment.

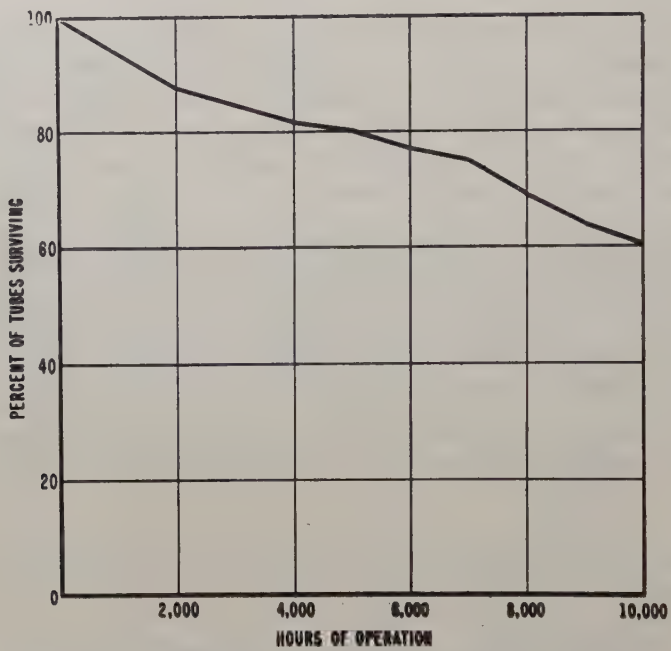

Fig. 3 - Survival pattern for all tubes in control test 27.

Figure 3 shows what the survival pattern looks like for the cumulation of all receiving tube types under observation in all equipments that formed a part of this particular control test. This curve fits quite well the theoretical exponential, whereas the curves for the individual tube types largely fit the theoretical normal.

These figures give some idea of where we stand today in tube reliability from an operational point of view. They demonstrate that tubes can be a vital, and yet dependable, factor in military electronics systems. They also demonstrate that tubes must be properly integrated into the design of electronic equipment in order to achieve a high order of reliability.

Tube Developments

In some instances, it would be helpful to stop scientific advancements for a while and concentrate on present-day problems. But all too often we find ourselves faced with the reality that just around the corner there are tube needs that can't be satisfied with the class of tubes now available. Something must be done to bring about a new order of tube performance.

The evolution of high-speed aircraft and guided missiles has presented such a problem. Their requirements for compactness and resistance to high temperatures and high accelerations have demanded a new look at the concepts used in the design and manufacture of tubes. To meet this need the military departments have worked with the tube industry on both short-range and long-range approaches to the problem. The short-range approach has been somewhat of a brute force nature in that it attempted to further refine and improve the design and manufacturing techniques for the currently used types of high quality tubes.

The approach consists largely of more rigid inspections and tests of both parts and assembled tubes. The long-range approach has been to design a family of tubes that are inherently more capable of satisfying missile and aircraft needs. Under military sponsorship, Sylvania Electric Products Inc. has been engaged in such an effort. Their engineers have designed a family of seven types to serve these needs. The designs were optimized in performance for the normal aircraft and missile circuit functions. The tubes have been designed with short, rigidly supported mount structures to withstand high accelerations. Spacings between interval elements have been kept as wide as possible to minimize the probability of internal shorts, even under adverse usage conditions. The tube elements are enclosed in subminiature T-3 envelopes of Pyrex glass construction. This will increase their ability to give satisfactory performance at ambient temperatures above those that limit the usefulness of conventional soft glass tubes. All seven types of tubes have been tooled for production. Several types are now being made in pilot production, and the remaining types will follow. Pilot production tubes are being carefully evaluated on both initial characteristic measurements and on various types of life tests to obtain data for developing MIL-E-1 procurement specifications. These specifications are expected to be available in midyear 1957. RETMA registration numbers have been assigned to Sylvania for the individual tube types.

The military services have also sponsored other long-range receiving-tube development programs. These efforts are resulting in tube designs that depart much from conventional design practices. Extensive use is being made of ceramic and metal as envelope materials. Additionally, the use of ceramic for spacer elements to separate the internal tube parts makes it possible to provide a family of tubes potentially capable of operation at ambient temperatures of 500°C and above. Under military sponsorship, Eimac-McCullough Inc. is developing a family of receiving tubes using these techniques. The tubes employ a planar design principle in which the ceramic spacer elements also form a part of the vacuum enclosure. It is quite obvious that the use of these new materials and new concepts of receiving-tube design will require new techniques for assembly and processing of the finished tubes. These techniques are being worked out concurrently with the advanced work on tube design.

Under military sponsorship, Sylvania has been engaged in the design and development of a family of receiving tubes that also makes extensive use of ceramic and metal parts. These tubes are potentially capable of operation under extreme conditions of temperature and acceleration. As a family of tubes they are unique in that their spacer elements are not a part of the vacuum enclosure, frame-type grids are employed and the tube physical configurations and external connections to the tube elements are quite similar to conventional miniature tubes. The family consists of nine different types, including two separate-cathode, twin-triode types. A large segment of the missile and aircraft elec-

tronics industry has been sampled with one of the tube types. No attempt will be made here to review other work of a similar nature that is commercially supported. Nevertheless, such activity is of great interest to the military departments.

PAST ACCOMPLISHMENTS

Improved Tubes

To arrive at our present position, we first needed a measurement on tube reliability in the field under typical field operating conditions. This required an independent mission to obtain and analyze dependable field data and to then draw significant conclusions. Aeronautical Radio provided this service. Upon determining the area and specific nature of tube weaknesses, a cooperative effort was undertaken with the tube manufacturing industry to correct the weaknesses. Field evaluations of the improved tubes were then made to determine the degree of improvement, if any, and what further improvements were necessary.

The Armed Services and the tube industry have made large financial investments in tube reliability efforts of the type just mentioned. We believe their policy has justified itself and will continue to do so.

Better Specifications

Along with our tube improvement efforts, there have been sincere and devoted attempts on the part of the government, the tube manufacturing industry and various tube user activities to better describe and control tube quality in military tube procurement specifications. These are not easy tasks, particularly if specification controls are based only on performance features that can be described and scientifically measured. Progress in this area has been of major significance.

Preferred Lists

Another major aid in obtaining tube reliability has been military imposition of various restrictions on the choice of tube types for new electronic equipment designs. While severe restrictions in the choice of tube types can impede progress in the equipment design field, a moderate degree of restriction is necessary. The military departments and the tube manufacturing industry are not equipped technically or economically to manufacture high-quality versions of every commercial tube type, which from the appearance of its technical data sheet appears to offer some marginal performance advantage. The cooperation of the electronics equipment industry in adhering to the spirit of military tube preferred lists has greatly assisted in improving tube reliability.

Applications Data

I wish to commend the many and varied efforts that have been made to effect a better understanding on the part of tube users of the performance capabilities and limitations of electron tubes. We appreciate the cooperative efforts of the tube manufacturing industry in providing the services of their applications engineers to assist military equipment designers in problems involving the utilization of tubes. Under the leadership of the Advisory Group on Electron Tubes (under the

Office of the Assistant Secretary of Defense for Research and Development), we have engaged this consulting service for the last several years to work with our equipment design contractors in reviewing tube applications in all of our Navy electronic equipment that is of major tactical importance or of potential large volume procurement. The other services have made similar use of this help.

The Armed Services have sought the assistance of both the tube manufacturing industry and various tube user activities to obtain data that could be used to describe tube performance under various typical field operating conditions. Under contracts with Sylvania, the General Electric Company, the Burroughs Corporation, and perhaps others, intensive studies are being made to determine tube deterioration rates under predetermined life-test conditions. The following variables are being induced either singly or in multiples: variations in heater or filament voltages, in plate and screen voltages, in plate and screen power dissipations, various grid pulse conditions, elevated ambient temperatures, simulated altitudes and various shock and vibration acceleration conditions. The work at Burroughs is concerned with the investigation of tube life under computer operating conditions. Aeronautical Radio also has been performing a valuable service to the military in the analysis of tube manufacturers' life-test data and, subsequently, in the preparation of material for tube applications manuals. This material describes tube performance variations with operating life, including rates of development of degradation features. Surely these supplemental efforts to assist tube users in a better understanding of tube behavior have helped much to obtain more reliable tube operation.

FUTURE TRENDS

The gradual deterioration of tube performance with operating hours is still a source of many problems in the operation and maintenance of military electronic equipment. Equipment faults that result from deteriorated tube performance are usually not easy to diagnose and correct. They often combine with some other adverse operational condition to result in an operator complaint of equipment performance that can't very well be duplicated by the maintenance technician. In his efforts to locate and correct these elusive difficulties, the maintenance technician often induces other potential faults. One problem leads to another until sometimes a dilemma results. This is evident in the observations made by Aeronautical Radio of the tube removal patterns and maintenance actions performed at various time intervals on military equipments.

Lower Deterioration Rates

You may ask, what has tube deteriorations got to do with this, particularly in the light of the very favorable tube performance that was illustrated in Fig. (1). To answer this question, let me make a couple of other remarks about the tube failure data that was illustrated on this graph. About 90 per cent of all tubes removed from that particular control test had measurable amounts of cathode interface resistance. The amount of resistance bore a relationship either to the change in transconductance that occurred during tube life or the change in peak emission capabilities of the tubes. These relationships will be expressed in a forthcoming report being prepared by Aeronautical Radio. During 11,000 hours operation of the AN/SPA-8A radar indicator, 29 per cent of the control test tubes initially installed were removed. This is quite gratifying except for the fact that it doesn't take very long to accumulate that number of hours on this equip-

ment. Neither is the equipment very critical of tube performance; as long as the tubes are warm, the equipment doesn't complain. In the AN/URT-2, 3 and 4 transmitters there was removed after 3,000 hours of operation 99 per cent of the control test tubes initially installed. In each of these two types of equipments (radar indicator and radio transmitter) the tube defects were largely in the categories of low emission or low transconductance and interelement leakages. These defects can be improved. They probably result from cathode temperatures and cathode materials that have been optimized for features other than long life. I would like to make a plea for lower cathode temperatures and for cathode materials less prone to interface formation.

Improved Specifications

Much room for improvement remains in military tube procurement specifications. We need to describe and control more effectively the life characteristics of tubes under pulsed operating conditions. This work is in progress. A much better job of describing and controlling tube performance under prolonged conditions of vibration acceleration is also needed. The vibration tests must either simulate or correlate quite well with the random acceleration times and intensities experienced in field service. Work along these lines is in progress and soon is expected to bear fruit. It is time that the military departments and the tube industry jointly take a good look at tube life test philosophies with a view to making some general improvements. A proper life test for tubes, or any other product, should evaluate defectives in a manner that gives considerations to at least four factors: (1) the time during the life test at which the defect occurred, (2) the nature of the defect, (3) the degree or extent of defectiveness and (4) the total number of defects. With few exceptions, our present life tests for reliable tubes do not give consideration to the time during the life test at which the defect occurred, nor do they consider the degree or extent of defectiveness. However, this situation does not exist completely without reason. Instrumentation for monitoring tube life tests would be required to accurately determine the job are not generally available at present. However, some progress is being made along these lines. The problems facing us are not insurmountable; they are no greater than those which we already have faced and overcome. With the continued use of objective foresight, determination and cooperation, progress can be assured.

EVALUATION OF TRANSISTOR LIFE DATA

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Poughkeepsie, New York

Summary -- The purpose of evaluating transistor life data is to make possible proper application, specification and design of transistors. There are many methods of testing and analyzing life characteristics. These methods are reviewed and discussed here from the standpoint of the user, with emphasis on a particular statistical approach.

Components are initially evaluated at different temperatures to determine such general characteristics as current gain and leakage currents in the collector and emittor cutoff region. Samples are also submitted to mechanical and environmental tests. Life tests are conducted at various temperature and power levels. As a control feature, shelf life tests are usually performed simultaneously. Data collected from life tests are recorded on punched cards. Each card contains all the data for a given transistor at a particular time during the life test. This information is used as the input for an electronic calculator by means of which statistical summaries can be computed. The use of calculators accelerates the evaluation period and therefore allows more data to be analyzed efficiently. This method permits either individual or group evaluation procedures. The results are presented on curves and charts.

In evaluating a new component, extensive life tests are run to obtain information about the rate of change of parameters. One phase of testing concerns the rate of degradation with time, for the purpose of setting design limit parameters as well as initial limits for purchase specifications. Another is running power dissipation tests at elevated temperatures to determine the maximum conditions that can be tolerated. Also, quality level is screened to check catastrophic failure rates and to assure a continued high product standard.

The large quantity of life tests that can be undertaken produces a tremendous amount of data and makes analysis an expensive and time-consuming task. This can cause inadequate summaries and, in some cases, complete loss of the individual data within the group tested. Adding mathematical rigor to the summaries becomes extremely complicated. For this reason, superficial judgement only is normally used. To solve this problem of controlling the data collected, a punch card system can be employed. From this system any needed sorting, summary or computation can be made, and individual data are always maintained and readily available.

TRANSISTOR LIFE TESTS

In the life tests of transistors, only certain parameters are generally measured. Preferably, these parameters are static (dc) measurements. For computer usage the most significant terms of interest are large signal alpha, collector to base cutoff current and emitter to base cutoff current. The latter are normally measured at both the nominal working voltage and the minimum voltage specified for breakdown. Room temperature measurements are made for the sake of simplic-

ity, although elevated temperatures are preferred. However, sample measurements are made to correlate to the elevated temperatures. Alpha measurements also can be made over a wide range of currents. Ordinarily, a low value of current is chosen for alpha measurements, because it tends to exhibit the greatest rate of change.

Two types of life tests, power dissipation and storage temperature, are conducted. Power dissipation tests are run at elevated temperature, usually with some cycling on and off of power. The latter tends to simulate actual machine performance. A shelf life test helps to serve as a control check on the other tests.

Prior to the life tests, a fairly complete characteristics check is made. This can be repeated at the end of testing to see whether characteristics not normally checked in life tests have been adversely affected. Also, mechanical and environmental tests are made to check the adequacy of the package as to seals, leads and the like.

DATA COLLECTION PROCEDURE

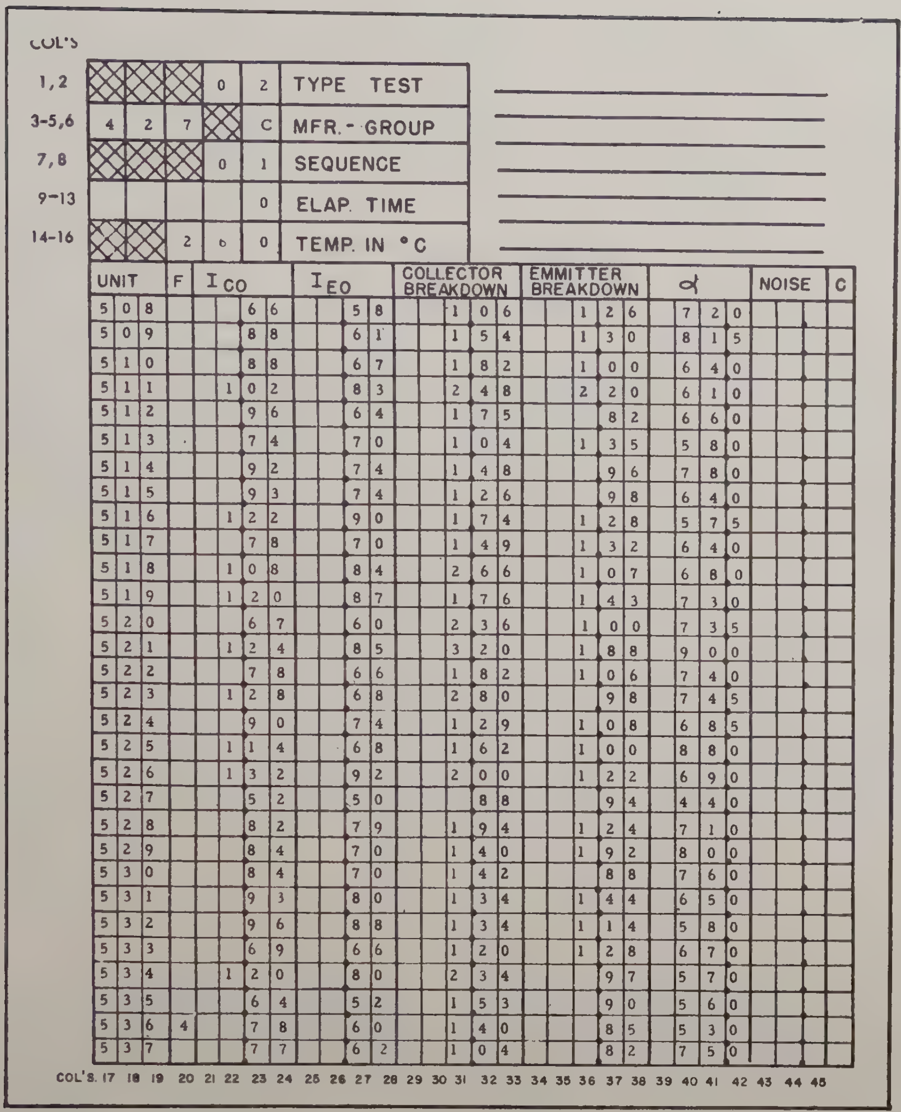
Currently, the data from the life tests are being collected by laboratory technicians, who must handle and measure each unit and also record its value. This method is repeated for each unit at different time increments throughout the test. The possibility of cutting test costs further is being explored. Automatic testers that will make the necessary tests and place data directly on punch cards are under consideration. An approach to this was discussed in a recent paper, "An Automatic Card Punching Transistor Test Set," by M. L. Embree and D. E. Williams, Bell Telephone Laboratories.* Automatic testing will further simplify handling procedure, because all units will be connected or soldered in a fixed position during the entire life test. This will minimize the amount of loss caused by lead breakage.

At present, the recorded data are transferred to punched cards. These in turn are fed into IBM accounting machines and computers for listings, tabulations and mathematical computations. Also available are X-Y recorders, which can plot curves or distributions directly from punch cards, and a digital keyboard, which can be used to plot curves directly.

A typical form sheet (Fig. 1) used by the laboratory technicians for recording measured values is designed so the recorded data can be punched easily into cards. The card columns into which these data are to be punched are indicated by corresponding numbers located on the upper left-hand side and along the bottom of the sheet. The block at the top left of Fig. 1 contains the sample identification in code plus the test sequence and indicates the elapsed time during which all items have been on life test.

Figure 2 is a typical punch card containing identification and the measured values of one unit at one time increment (as shown in Fig. 1). It requires one card at each time increment to record the complete test history of each unit. With many units per sample and several time increments throughout the test, hundreds of cards are necessary to record the complete data of any life test.

*Published in the Proceedings of the 1956 Electronics Components Symposium.



COL'S						
1,2				0	2	TYPE TEST
3-5,6	4	2	7		C	MFR.- GROUP
7,8				0	1	SEQUENCE
9-13					0	ELAP. TIME
14-16			2	6	0	TEMP. IN °C

UNIT	F	I_{CO}	I_{EO}	COLLECTOR BREAKDOWN	EMMITTER BREAKDOWN	α	NOISE	C
508		66	58	106	126	720		
509		88	61	154	130	815		
510		88	67	182	100	640		
511		102	83	248	220	610		
512		96	64	175	82	660		
513		74	70	104	135	580		
514		92	74	148	96	780		
515		93	74	126	98	640		
516		122	90	174	128	575		
517		78	70	149	132	640		
518		108	84	266	107	680		
519		120	87	176	143	730		
520		67	60	236	100	735		
521		124	85	320	188	900		
522		78	66	182	106	740		
523		128	68	280	98	745		
524		90	74	129	108	685		
525		114	68	162	100	880		
526		132	92	200	122	690		
527		52	50	88	94	440		
528		82	79	194	124	710		
529		84	70	140	192	800		
530		84	70	142	88	760		
531		93	80	134	144	650		
532		96	88	134	114	580		
533		69	66	120	128	670		
534		120	80	234	97	570		
535		64	52	153	90	560		
536	4	78	60	140	85	530		
537		77	62	104	82	750		

COL'S. 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45

Fig. 1

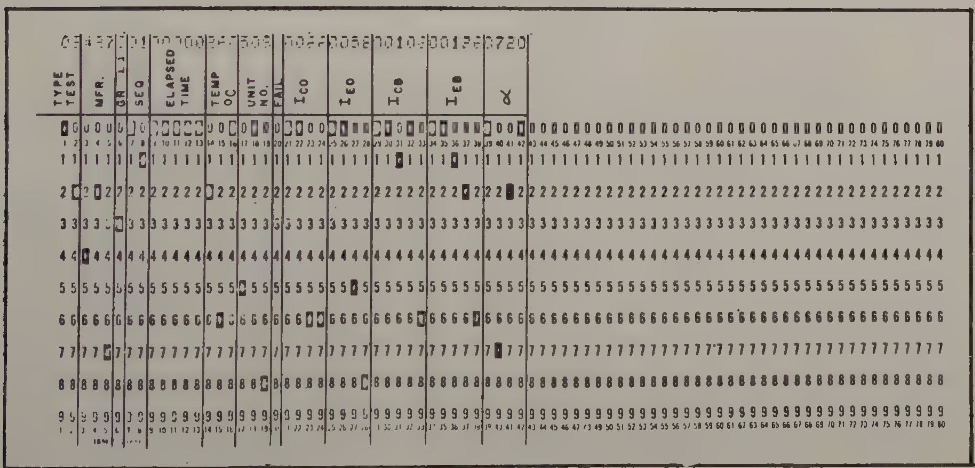


Fig. 2

It is now possible to generate listings for any one time for all units on test, as indicated by Fig. 3. This table shows the measured parameters at a single time for all units on test. The failure column contains a code for the type of failure encountered, which is described later in this paper. A list can also be made of a single parameter for all units for the entire time on test, as shown in Fig. 4.

STATISTICAL PROCEDURE

Once the recorded data have been listed, consideration must be given to the results desired, such as degradation rate of parameters with time, maximum tolerable environmental conditions, quality level or reliability. In terms of quality level or reliability, the interest is in the number and types of failures that occur over a period of time. Unit failures are classified into categories such as open, shorts, mechanical and catastrophic. Mechanical failures are not considered as actual failures, because the defects are usually caused by handling as in the case of broken leads. If mechanical failures are caused by defective workmanship, they become part of a separate analysis consisting of pull and bend tests, vibration, temperature shock and humidity cycling. In life tests mechanical failures are removed, and the sample size is adjusted accordingly.

Any units exceeding previously specified end-of-life values for each parameter are classified as catastrophic failures. End-of-life values are initially predicated by experience in environmental conditions encountered, manufacturers' experience and life tests conducted previously at IBM. Semiconductor ratings are

Type Test	Mfr.	Group	Sequence	Elapsed Time	Temp. in °C	Unit No.	Failure	I_{co}	I_{eo}	I_{cb}	I_{eb}	Alpha $\left(\frac{1-alpha}{2}\right)$
02	427	C	01	0	26.0	508		.66	.58	1.06	1.26	72.0
02	427	C	01	0	26.0	509		.88	.61	1.54	1.30	81.5
02	427	C	01	0	26.0	510		.88	.67	1.82	1.00	64.0
02	427	C	01	0	26.0	511		1.02	.83	2.48	2.20	61.0
02	427	C	01	0	26.0	512		.96	.64	1.75	.82	66.0
02	427	C	01	0	26.0	513		.74	.70	1.04	1.35	58.0
02	427	C	01	0	26.0	514		.92	.74	1.48	.96	78.0
02	427	C	01	0	26.0	515		.93	.74	1.26	.98	64.0
02	427	C	01	0	26.0	516		1.22	.90	1.74	1.28	57.5
02	427	C	01	0	26.0	517		.78	.70	1.49	1.32	64.0
02	427	C	01	0	26.0	518		1.08	.84	2.66	1.07	68.0
02	427	C	01	0	26.0	519		1.20	.87	1.76	1.43	73.0
02	427	C	01	0	26.0	520		.67	.60	2.36	1.00	73.5
02	427	C	01	0	26.0	521		1.24	.85	3.20	1.88	90.0
02	427	C	01	0	26.0	522		.78	.66	1.82	1.06	74.0
02	427	C	01	0	26.0	523		1.28	.68	2.80	.98	74.5
02	427	C	01	0	26.0	524		.90	.74	1.29	1.08	68.5
02	427	C	01	0	26.0	525		1.14	.68	1.62	1.00	88.0
02	427	C	01	0	26.0	526		1.32	.92	2.00	1.22	69.0
02	427	C	01	0	26.0	527		.52	.50	.88	.94	44.0
02	427	C	01	0	26.0	528		.82	.79	1.94	1.24	71.0
02	427	C	01	0	26.0	529		.84	.70	1.40	1.92	80.0
02	427	C	01	0	26.0	530		.84	.70	1.42	.88	76.0
02	427	C	01	0	26.0	531		.93	.80	1.34	1.44	65.0
02	427	C	01	0	26.0	532		.96	.88	1.34	1.14	58.0
02	427	C	01	0	26.0	533		.69	.66	1.20	1.28	67.0
02	427	C	01	0	26.0	534		1.20	.80	2.34	.97	57.0
02	427	C	01	0	26.0	535		.64	.52	1.53	.90	56.0
02	427	C	01	0	26.0	536	4	.78	.60	1.40	.85	53.0
02	427	C	01	0	26.0	537		.77	.62	1.04	.82	75.0

Fig. 3

TRANSISTORS

I_{CO} in μa

Identification	Unit No.	Seq.	1	2	3	4	5	6	7	8	9	10
		Hours	0	25	50	75	200	500	750	1000	1500	2000
02-427-C	508		.66	.76	.67	.65	.64	.60	.54	.83	.68	.70
	509		.88	.89	.92	.90	.94	.88	.80	.88	.80	.72
	510		.88	1.12	.94	.90	.92	1.03	.80	.88	.78	.82
	511		1.02	1.34	1.11	1.09	1.12	1.16	1.10	1.30	1.22	1.07
	512		.96	1.08	.94	.94	.92	.92	.86	.93	.82	.86
	513		.74	.84	.80	.78	.86	1.12	1.06	1.08	.99	.96
	514		.92	1.00	.92	.88	.92	.86	.80	.94	.82	.94
	515		.93	1.26	1.02	1.17	.98	1.00	.82	.92	.78	.82
	516		1.22	1.22	1.24	1.32	1.32	1.36	1.02	1.18	.96	1.01
	517		.78	.76	.78	.78	.74	.84	.72	.77	.66	.67
	518		1.08	1.13	1.22	1.07	1.18	1.24	1.28	1.60	1.38	1.16
	519		1.20	1.42	1.42	1.34	1.30	1.21	1.10	1.26	1.08	1.11
	520		.67	.69	.66	.69	.64	.60	.54	.66	.56	.54
	521		1.24	1.39	1.32	1.32	1.36	1.28	1.14	1.37	1.14	1.16
	522		.78	.85	.84	.81	.82	.78	.76	.82	.78	.74
	523		1.28	1.34	1.28	1.32	1.20	1.16	1.18	1.30	1.08	.98
	524		.90	.94	1.02	1.00	.96	.90	.86	.90	.82	.74
	525		1.14	1.22	1.22	1.12	1.16	1.19	1.32	1.24	1.15	1.02
	526		1.32	1.17	1.16	1.06	1.56	1.35	1.48	1.40	1.27	1.05
	527		.52	.43	.44	.38	.42	.36	.38	.46	.38	.38
	528		.82	.92	.86	.82	.78	.78	.80	.80	.73	.76
	529		.84	1.16	.97	.98	.92	.94	.95	.96	.84	.88
	530		.84	.72	.73	.66	.68	.65	.66	.90	.76	.86
	531		.93	1.02	1.04	1.00	1.18	.98	.94	1.06	.94	1.10
	532		.96	1.02	1.06	.95	1.02	.92	.98	.96	.84	.82
	533		.69	.86	.93	.82	.94	.83	.93	.86	.82	.70
	534		1.20	1.38	1.26	1.26	1.26	1.25	1.32	1.30	1.12	1.12
	535		.64	.50	.48	.46	.45	.40	.46	.48	.51	.54
	537		.77	.80	.80	.78	.80	.80	1.20	.82	.72	.64

N = 29

Fig. 4

specified for 20,000 hour life; allowable catastrophic failure rates by an Approved Quality Level per 1,000 hour A.Q.L. limits are determined by the number of semiconductors used in a production machine, plus several other factors. Failures that occur during life test are classified, and all but catastrophic failures are removed from test. Units that are catastrophic remain on test to determine their leveling-off points and are removed when they become open or shorts. Catastrophics are, however, excluded from computed data and analyzed separately.

With reference to the parameters being analyzed, the end-of-life limits are all maximum except current gain. Generally all limits are single-ended, and hence only unit distribution relationships to the limits described are needed. The standard deviation concept describes the dispersion of a series about a point of central tendency. This is used to generate two standard deviations from the mean in the direction of end-of-life limits. This distance of two standard deviations from the mean includes approximately 95 per cent of the sample.

Graphs are prepared to illustrate the results of each parameter trend. In the statistical analysis the interest is primarily in the total sample instead of the individual unit. Because of this, graphs are drawn that exhibit the extremes, mean and mean plus or minus two standard deviations (depending upon limit value) at each time increment. The line of regression or trend line about the mean and mean plus or minus two standard deviations is also described.

In most applications the linear trend has proven adequate. However, the curves are calculated for both the linear and curvilinear case.

Since all the individual data are on punch cards, any of the normal statistical formulas can be derived from an IBM computer which has been mathematically programmed, as shown in Fig. 5. Collector cutoff current is indicated for each unit time over a 2,000 hour life test period. Not all of the derivations described may be useful, but they are shown for the sake of completeness. In this

02-427-C

COMPUTED VALUES FOR I_{co}

Sequence	1	2	3	4	5	6	7	8	9	10
Hours	0	25	50	75	200	500	750	1000	1500	2000
High	1.32	1.42	1.42	1.34	1.56	1.36	1.48	1.60	1.38	1.16
Low	0.52	0.43	0.44	0.38	0.42	0.36	0.38	0.46	0.38	0.38
Range	0.80	0.99	0.98	0.96	1.14	1.00	1.10	1.14	1.00	0.78
Mean	0.924	1.008	0.967	0.942	0.965	0.944	0.924	0.995	0.877	0.858
Median	0.90	1.02	0.94	0.94	0.94	0.92	0.93	0.93	0.82	0.86
Variance	0.045	0.070	0.060	0.062	0.073	0.070	0.073	0.073	0.054	0.041
Standard Deviation	0.213	0.264	0.244	0.249	0.271	0.265	0.271	0.271	0.232	0.204
Mean + Sigma	1.14	1.27	1.21	1.19	1.24	1.21	1.20	1.27	1.11	1.06
Mean + 2 Sigma	1.35	1.54	1.46	1.44	1.51	1.48	1.47	1.54	1.34	1.27
Mean + 3 Sigma	1.56	1.80	1.70	1.69	1.78	1.74	1.74	1.81	1.57	1.47
Mean - Sigma	.71	.74	.72	.69	.69	.68	.65	.73	.65	.65
Mean - 2 Sigma	.50	.48	.48	.44	.42	.41	.38	.46	.41	.45
Mean - 3 Sigma	.29	.22	.23	.19	.15	.15	.11	.19	.18	.25
Coefficient of Variation	23.01	26.21	25.27	26.54	28.08	28.10	29.33	27.15	26.50	23.75
Third Moment	0.002	-0.005	-0.003	-0.003	0.000	-0.007	-0.000	0.003	0.002	-0.003
Fourth Moment	0.004	0.011	0.009	0.009	0.013	0.012	0.012	0.013	0.007	0.004
Kurtosis	-0.823	-0.645	-0.442	-0.375	-0.342	-0.447	-0.523	-0.303	-0.288	-0.593
Skewness	0.245	0.270	0.234	0.181	0.011	0.376	0.022	0.176	0.191	0.314

Fig. 5

case an elevated temperature power dissipation showed little degradation of cutoff current and little change in the shape of the distribution. Some of the variations indicated were caused primarily by instrument tolerances and ambient temperature changes. Measuring equipment is all accurate to within 1/2 per cent or better, and an air-conditioned atmosphere controls the working ambient. Equipment should be of a type that minimizes the judgement of the operator in collecting data.

A typical life trend curve is exhibited by Fig. 6 for collector cutoff current from the data just shown. This curve is a reversal of the normally expected trend of increasing cutoff current. Figure 7 indicates the current gain trend for a power dissipation life test in the fashion just described. The common emitter current gain on a 6,400 hour power dissipation life test for some units made in the last quarter of 1954 is described in Fig. 8. Present transistors exhibit less degradation than is shown in this figure.

There are many types of parameter changes which cannot be described by statistical calculation. An example is the current gain of transistors over a large range of collector currents. To treat this with normal methods is a tedious and time-consuming measurement problem. Figure 9 indicates the change of current gain for a typical high, low and average unit over two time intervals. For this purpose an X-Y recorder was used, in which the transistors in a common emitter state had a linear current sawtooth applied to the base, and the resultant collector was measured. The solid curved line indicates the characteristics at the

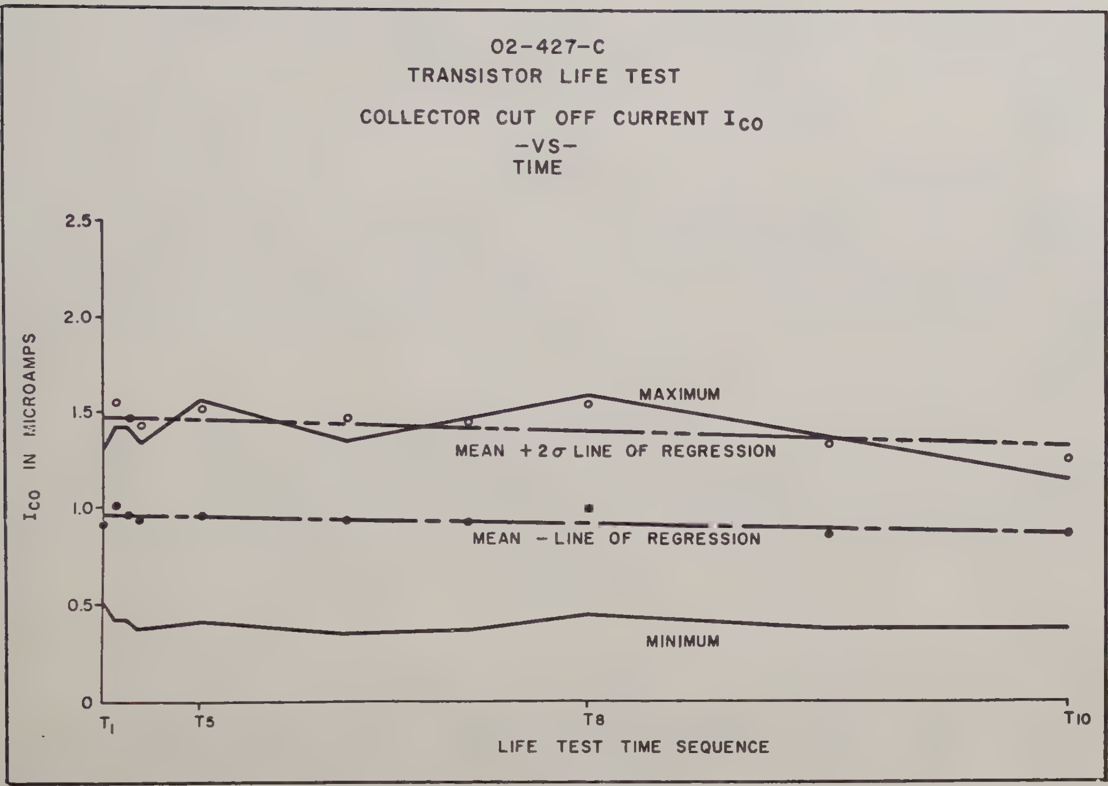

02-427-C
TRANSISTOR LIFE TEST
COLLECTOR CUT OFF CURRENT I_{CO}
-VS-
TIME
2.5
2.0
1.5
1.0
0.5
0
I_{CO} IN MICROAMPS
MAXIMUM
MEAN $+2\sigma$ LINE OF REGRESSION
MEAN - LINE OF REGRESSION
MINIMUM
T_1
T5
T8
T10
LIFE TEST TIME SEQUENCE

Fig. 6

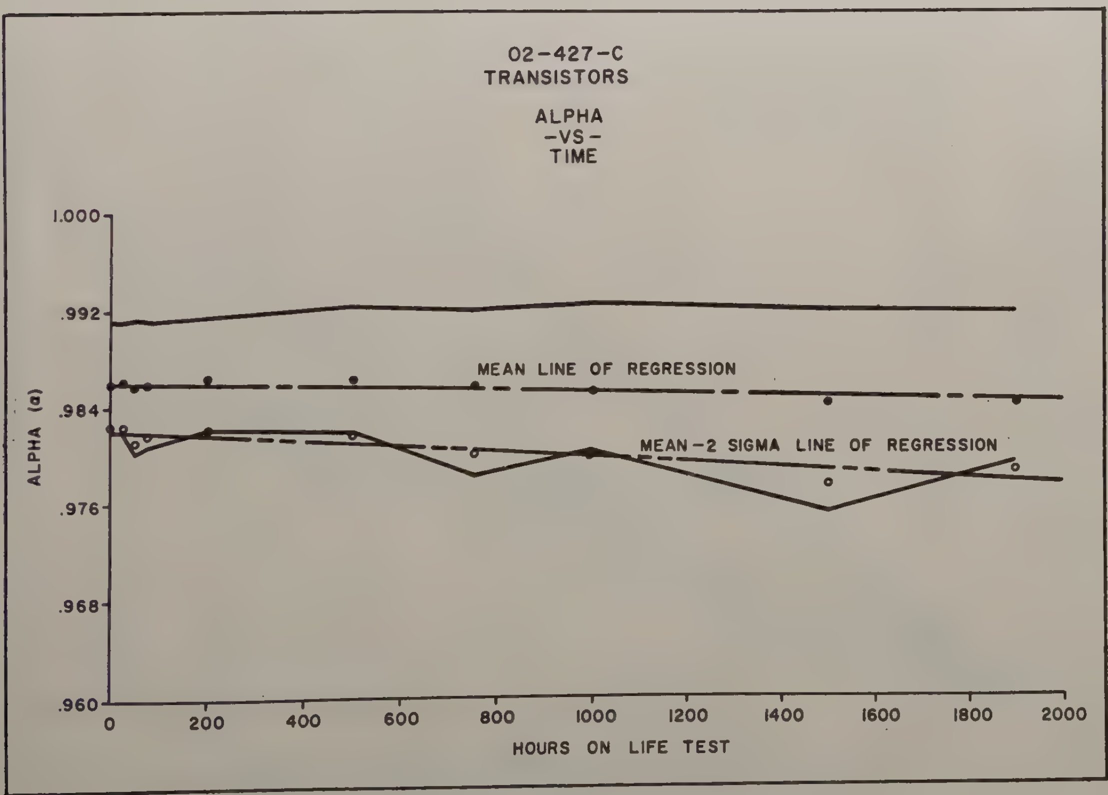
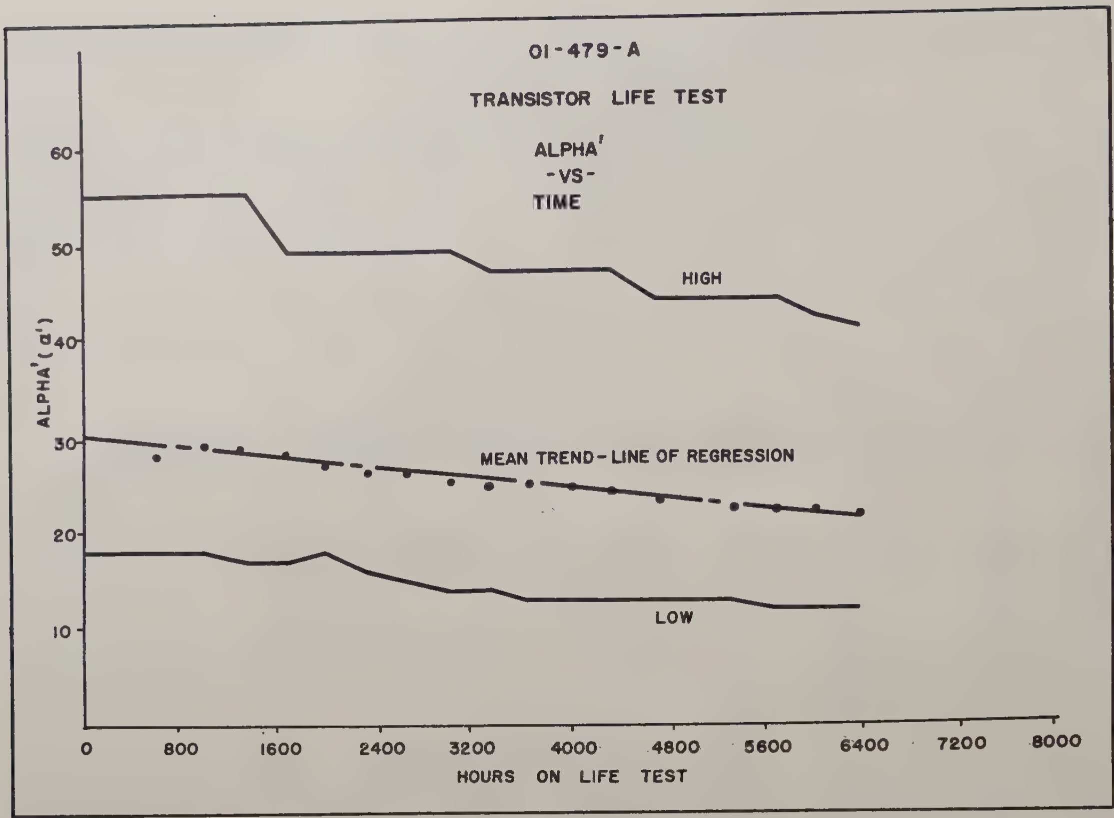
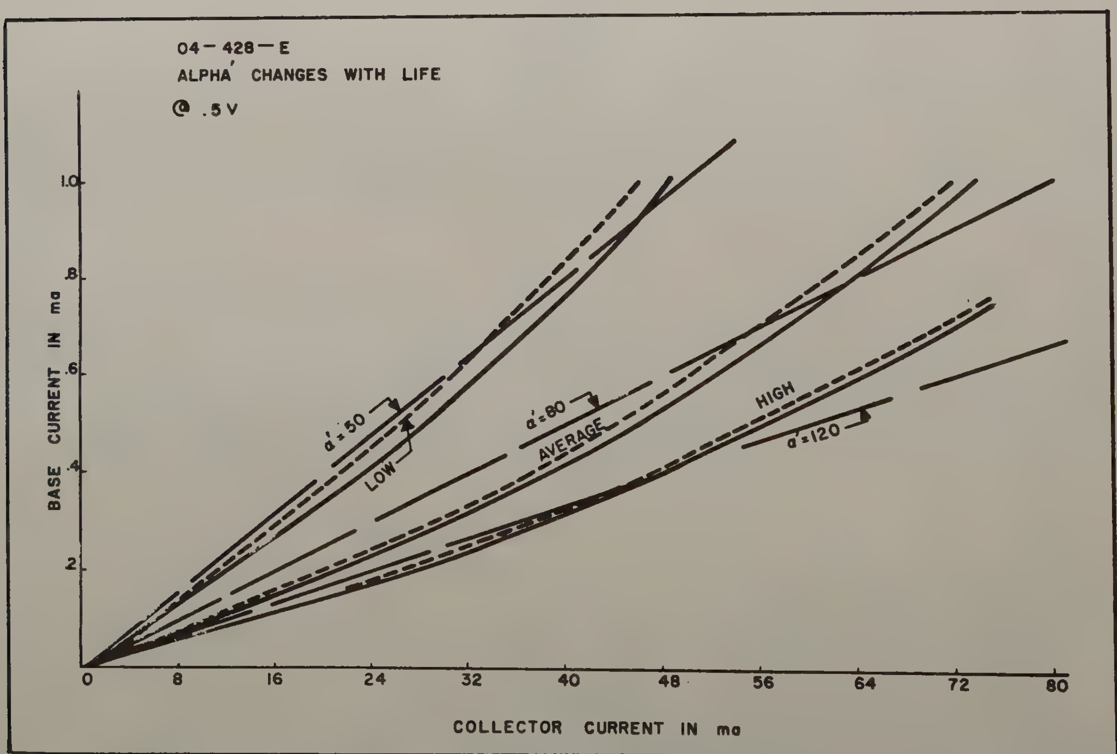

02-427-C
TRANSISTORS
ALPHA
-VS-
TIME
1.000
.992
.984
.976
.968
.960
ALPHA (α)
MEAN LINE OF REGRESSION
MEAN-2 SIGMA LINE OF REGRESSION
0
200
400
600
800
1000
1200
1400
1600
1800
2000
HOURS ON LIFE TEST

Fig. 7



01-479-A
TRANSISTOR LIFE TEST
ALPHA'
-VS-
TIME
HIGH
MEAN TREND-LINE OF REGRESSION
LOW
ALPHA' (α')
60
50
40
30
20
10
0
800
1600
2400
3200
4000
4800
5600
6400
7200
8000
HOURS ON LIFE TEST

Fig. 8



04-428-E
ALPHA' CHANGES WITH LIFE
@ .5V
α'=50
LOW
α'=80
AVERAGE
HIGH
α'=120
BASE CURRENT IN ma
1.0
.8
.6
.4
.2
0
8
16
24
32
40
48
56
64
72
80
COLLECTOR CURRENT IN ma

Fig. 9

initial time measured, and the broken curved line indicates the value at an extended period of time. The straight lines indicate typical values of common emitter current gain through the range. Several useful items of information can be derived which are not readily ascertained from normal statistical analysis.

The Appendix contains a description of the statistical procedures, together with the formulas used for calculation. Correlation studies of parameters are also being made in order to observe interrelationships of parameters measured either initially or with life. Examples of these are the relationships of fundamental measurements to circuit performance, or the relation of power dissipation life test to junction temperature life test.

ACKNOWLEDGEMENT

We wish to thank the IBM Computing Laboratory under the direction of W. G. Bouricius and especially the statistical programmers L. Ravesloot and J. Cooper, for the very capable assistance they have given us.

APPENDIX

Statistical Procedure and Formulas

Figure 10 lists the simplified formulas used to describe the following terms.

The range is the difference between the high and low values.

The arithmetic mean is a calculated average determined by the value of every item in the distribution and is the most commonly used statistic. Its one disadvantage

N = Total occurrences

$N-1$ = Used for correction or degrees of freedom for small samples

X_i = Unit Value

$\sum$ = Summation of -

Mean $(\bar{X}) = \dfrac{\sum(X_i)}{N}$

$$\left.\begin{array}{l}\text{Variance - - - } S^2 \\ \text{Second Moment } -\mu_2\end{array}\right\} \frac{\sum(X_i-\bar{X})^2}{N-1}$$

Standard Deviation $(\sigma) = \sqrt{S^2}$

Standard Error $(\sigma_{\bar{X}}) = \dfrac{\sigma}{\sqrt{N}}$

Coefficient of Variation $(V) = \dfrac{\sigma}{\bar{X}}$

Third Moment $(\mu_3) = \dfrac{\sum(X_i-\bar{X})^3}{N-1}$

Fourth Moment $(\mu_4) = \dfrac{\sum(X_i-\bar{X})^4}{N-1}$

Peakedness or Kurtosis $(\beta-3) = \dfrac{\mu_4}{\mu_2^2} - 3 = \dfrac{\mu_4}{\sigma} - 3$

Skewness $(a_3) = \sqrt{\dfrac{\mu_3^2}{\mu_2^3}} = \dfrac{\mu_3}{\sigma^{3/2}}$

Fig. 10 - Formulas used for distribution analysis.

is that its value may be greatly distorted by extreme values, particularly with small sample sizes. Consequently, a minimum sample size of 40 is considered suitable, if this can be employed economically.

The median is an average of position, reached by arranging values according to magnitude and then recording the size of the middle value. The median has the advantage of being easy to calculate. It is not distorted by extremes and is therefore more typical of the values of a series that are closely related. It is used generally for percentile and not for normal statistical computations. When the mean and the median lie close together, a rough indication of normal distribution is assured.

Variance or second moment is the sum of the squares of the deviations from the mean. It indicates how the observations are spread out from the arithmetic mean. A large value indicates that measurements are distant from the mean; a small value shows they are close to it. Because this is almost the mean of the squares of the deviation, it is occasionally referred to as the mean square deviation. The term is only significant for future formulas and is not generally important by itself.

Standard deviation is the root mean square of the variance, obtained by taking the square root of the variance. It is the most widely used measure of dispersion. A distance of ± 1 standard deviation from the mean includes approximately 68 per cent of all the values in the distribution. A distance of ± 2 standard deviations includes approximately 95 per cent of the values, and ± 3 standard deviations includes 99.7 per cent of the values. This is generally considered a standard measurement, and most future references are to it.

Coefficient of variation is the standard deviation divided by the mean, with results in terms of a per cent. Because standard deviation is an absolute measure, it cannot always be used significantly for comparison between different lots. The coefficient of variation allows dispersion to be compared to the size of the average about which it is measured.

Standard error is calculated by dividing the standard deviation by the square root of the total number of units in the sample. Since the sample mean is an estimate of the population mean, the standard error implies that the population mean will not vary from the sample mean by more than 3 standard errors in 99 chances in 100.

Moments are used to determine how the distribution deviates from the normal curve. A frequency distribution can be analyzed more accurately if certain moments of the distribution are computed. The most important moments are those measured with the mean as the origin. The first moment or average deviation is always zero, and the second moment or variance has already been described. The third moment is the sum of the cubes of the deviations divided by the occurrences, and the fourth moment is the fourth power of the deviations divided by the occurrences. The peakedness or kurtosis of the curve tells how far the distribution peak deviates from the normal curve peak. It is measured by dividing the fourth moment by the standard deviation and subtracting 3. A normal peak will have a value 0. A positive value indicates higher peakedness, and a negative value indicates a flatter curve.

Skewness is the degree of distortion from symmetry exhibited by a frequency distribution. It is measured by dividing the third moment by the 3/2 power of the standard deviation. A positive value indicates that the distribution is skewed to the right, and a negative value indicates the skewness is to the left. Zero indicates a normal curve.

Two methods of identifying the rate of change of distributions with life are considered below: the linear and the nonlinear trend line, sometimes called the line of regression.

The linear trend is a straight line which indicates the movement of a series of points as they vary with time. The points could be the arithmetic means, median, the mean plus two standard deviations already calculated or any other points of interest. The linear trend is calculated from the least squares method, where time is one variable and unit measurement, the other. The formulas used to compute straight line trend, as well as standard error, are shown in Fig. 11. The

Linear Trend Or Line of Regression: $Y' = a + bX'$

$$\left.\begin{aligned} \Sigma(Y) &= Na + b\Sigma(X) \\ \Sigma(XY) &= a\Sigma(X) + b\Sigma(X^2) \end{aligned}\right\} \text{Solve Simultaneously For } a \text{ and } b$$

X = Time Variable
Y = Unit Value (Mean at each time increment)
N = Number of Y units

Substitute a and b values in formula

$Y' = a + bX'$

$Y'o = a$ when $X' = o$ Time

$Y'n = a + bX'n$ when $X' = n$ Time

Standard Error of Estimate: $$Sy = \sqrt{\frac{\Sigma(Y-Y')^2}{N}}$$

Fig. 11 - Formulas for life test analysis.

Non-Linear Trend or Line of Regression: $Y' = a + bX' + cX'^2$

$$\left.\begin{aligned} \Sigma(Y) &= Na + b\Sigma(X) + c\Sigma(X^2) \\ \Sigma(XY) &= a\Sigma(X) + b\Sigma(X^2) + c\Sigma(X^3) \\ \Sigma(X^2Y) &= a\Sigma(X^2) + b\Sigma(X^3) + c\Sigma(X^4) \end{aligned}\right\} \text{Solve simultaneously for } a, b, \text{ and } c$$

X = Time Variable
Y = Unit Valve (Means)
N = Number of Y Values

Substitute a, b, and c Values in Formula

$Y' = a + bX' + cX'^2$

$Y'o = a$ when $X = O$ Time

$Y'n = a + bX' + cX'^2$ when $X' = n$ Times

Non-Linear Standard Error of Estimate: $$Sy = \sqrt{\frac{\Sigma(Y-Y')^2}{N}}$$

Fig. 12 - Formulas for life test analysis.

standard error of estimate defines the standard deviations about the trend line. Since the line of regression of the sample is an estimate for the population line of regression, the standard error of estimate forecasts that the population line of regression will fall in an area described by 3 standard errors from the sample line of regression 99.7 per cent of the time.

The nonlinear trend is sometimes preferred to a straight line trend. The latter does not always describe satisfactorily the association between variables. Frequently the relationship is curved. One of the more common curves is a parabola, although any order of curve can be calculated. The formulas for these relationships, as well as the nonlinear standard error of estimate, are described in Fig. 12. The nonlinear standard error has the same significance as for the linear case.

ON THE MEASUREMENT OF COMPONENT RELIABILITY

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As a user of components, RCA has been keenly interested in techniques which could be employed to obtain components having a desired or at least known reliability level. This has led to many studies of state of the art, failure reporting systems, required reliability levels, methods of specifying our requirements and, ultimately, to the Herculean task of reliability measurement. This paper deals with the last.

It has become necessary to provide failure-rate information, in numbers, not generalities, to the equipment designers in order that they can arrive at balanced system designs satisfying system life requirements. Data which have been in use in RCA were based on some measured failure rates extrapolated in terms of voltage, temperature, current or other controlling parameters. Sufficient information has been available to establish, with usable confidence, the general trend of failure rate of a given component type as a function of a controlling parameter, such as temperature. Many rough estimates were required but the effectiveness of the totality of failure-rate information has been proven for systems using a variety of components in large numbers. However, to suggest that this proves that each failure-rate value assumed for a component is accurate is not realistic. These data were obtained on many samples obtained from many sources. Perhaps the most useful information derived from these data was that which led to the general shape of the failure rate vs. stress curves; e.g., the failure rate for paper capacitors seems to vary as the fifth power of applied voltage. To be sure, this isn't the case for all samples or for all paper. Yet when this type of guidance is used to arrive at an over-all equipment mean-life prediction, it seems to hold up quite well.

From a measurements point of view, this suggests that testing time can be shortened by extrapolating, that is, by increasing the stress considerably beyond the required operating stress. This approach has been discussed often and considered to be valid only after large quantities of test samples have been evaluated and a decisive correlation is proven, component by component, lot by lot. I agree with this as it applies to a vendor who manufactures a specific type of component and is concerned about obtaining a correct measurement of the failure rate of his product. Nevertheless, it is entirely possible that a user may employ extrapolation analysis to a wide variety of components and arrive at a totality of conclusions as valid as equipment mean-life predictions have been.

Let's make this assumption and look into the matter further. It goes without saying that the life test is the only widely accepted test for predicting the life of a component in the equipment and, further, that the measurement of life of highly reliable components either requires long test periods, very large numbers of samples, or both. By testing components under extraordinary stress, the testing time can be shortened. To illustrate how much time improvement could be obtained, the situation for a few common components has been tabulated in Table I.

TABLE I

Sample Conditions for Accelerated Tests

	Rating	Test	Estimated Failure Acceleration
Mica capacitors	500v, 85°C	550v, 100°C	10
Paper capacitors	400v, 85°C	440v, 110°C	10
Wire wound resistors	15w, 85°C	22w, 85°C	2
Composition resistors	1w, 70°C	1w, 115°C	10

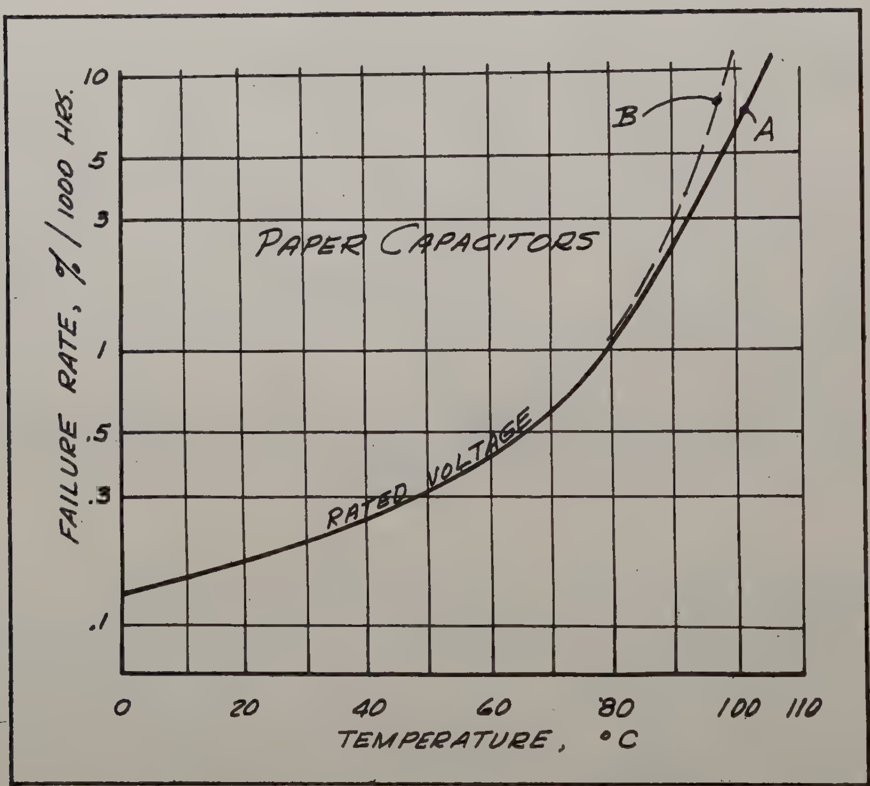

Fig. 1

These limitations in stress conditions are reached purely from considerations of the nature of the failure rate vs. stress curves (Fig. 1). As an example, for paper capacitors the failure rate vs. temperature curve is labeled A (this curve being a nominal one and not applicable to every specific case). Curve B is an expected departure. The slope of A and B at 100°C differ by over 2 to 1. By assuming the characteristics of our material, we can much too easily carry our extrapolation so far that the measured response is an unduly critical function of the controlled stress -- in this case, temperature. The two curves will yield

results differing over 2 to 1, further aggravated by considerable difficulty in controlling and measuring component ambient temperature under any but carefully monitored laboratory situations. Generally, it seems that a 10 to 1 time acceleration is about all that could be indulged in on a purely extrapolation basis. It should be noted that extreme accelerations aren't made on an extrapolation basis but are proven, item by item, or only used on a relative basis. MIL specifications call for as high as three times rated voltage, but don't identify the failure rate that would be assured.

What advantages would this give us in our number of samples vs. time? We hope soon to be able to buy capacitors having a failure rate in the order of .05 per cent per 1,000 hours, whereas today the same stress would provide only about 1 per cent per 1,000 hours. For the former level, we would need to use 4,600,000 sample hours with no failures and in the latter 230,000 sample hours with no failures with a 90 per cent users confidence level (based on assumption of uniform failure rate). This is required where we place the components on test at their ratings and, where we desire a mean life of 1,000 hours, we would test for 1,000 hours and permit no failures. On the same basis, under accelerated conditions we would use the same number of samples and test 100 hours and permit no failures, or reduce the number of samples and test for a longer period of time.

We feel this sample selection approach can be improved considerably. First of all, we have allowed no failures and so there is only a measure of minimum mean life. If the tests are designed so that all fail, specific life information is potentially obtained from each sample tested. This means destructive testing and correlation must be obtained between straight life test and accelerated and destructive tests. Also, sequential testing techniques when used would reduce the testing performed on unsatisfactory lots. Further, a study of the distribution of failures seems particularly significant since this gives a feeling for the extent of process control that the vendor does or does not maintain and for the uniformity of failure rate.

If we consider a component as an assemblage of materials and then examine these materials in order to piece together the failure contributions of the parts, some very helpful information may be obtained, depending on the component involved. In the case of a relay which involves many materials and tolerances, and which may have a relatively complex failure sequence, a materials approach to life prediction or measurement would not be very promising. In instances where a material application is dominant, however, such an approach could be useful. Let's take a cable as an example of a material used where the characteristics of the material are rather dominating.

We had occasion to study rather extensively the nature of failure of a rubber dielectric high-voltage cable. Although the cable was of a new design, materials and processes which had been in use for years were employed. This cable consistently did not survive more than a few hours of use in the equipment although its design was considered to be quite conservative. An old problem, a lack of adequate curing of the dielectric at an elevated temperature, was found to be the cause. However, in searching for the difficulty, we arrived at very practical and useful quality control criteria and were able to relate these criteria to operating life, at least to a useful degree.

Studies were made of the leakage current or insulation resistance of short lengths of various samples of cable. First, the voltage coefficient of insulation resistance was observed (Fig. 2). There is clearly a sharp difference between the two test results. Both were made on the sample as initially submitted. The upper curve resulted after the cable received additional curing. It will be noted that these are nondestructive measurements. Since the leakage current was found to be somewhat erratic, it was monitored on a recorder, the results of which can be seen in Fig. 3. The upper chart was made before the cable was cured and shows a leakage current of 25 ua and a noise level of about 7.5 peak-to-peak. The lower chart shows a leakage current of 1.5 ua and a noise variation of about 0.2 ua. There was a reduction in leagage current of about 17 to 1 and a reduction in current variation of about 40 to 1. There was a corresponding reduction in field failures of over 10 to 1.

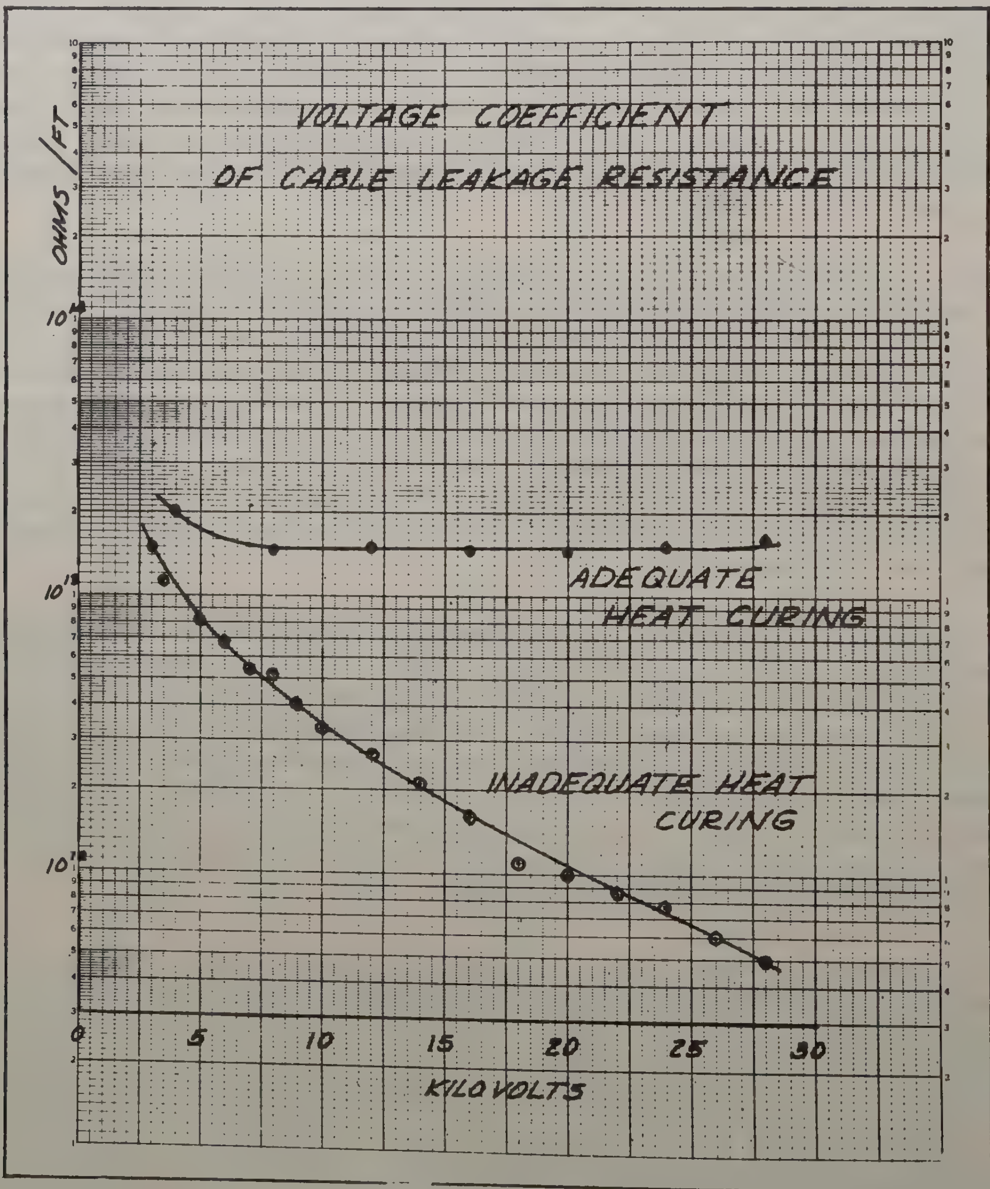

Fig. 2

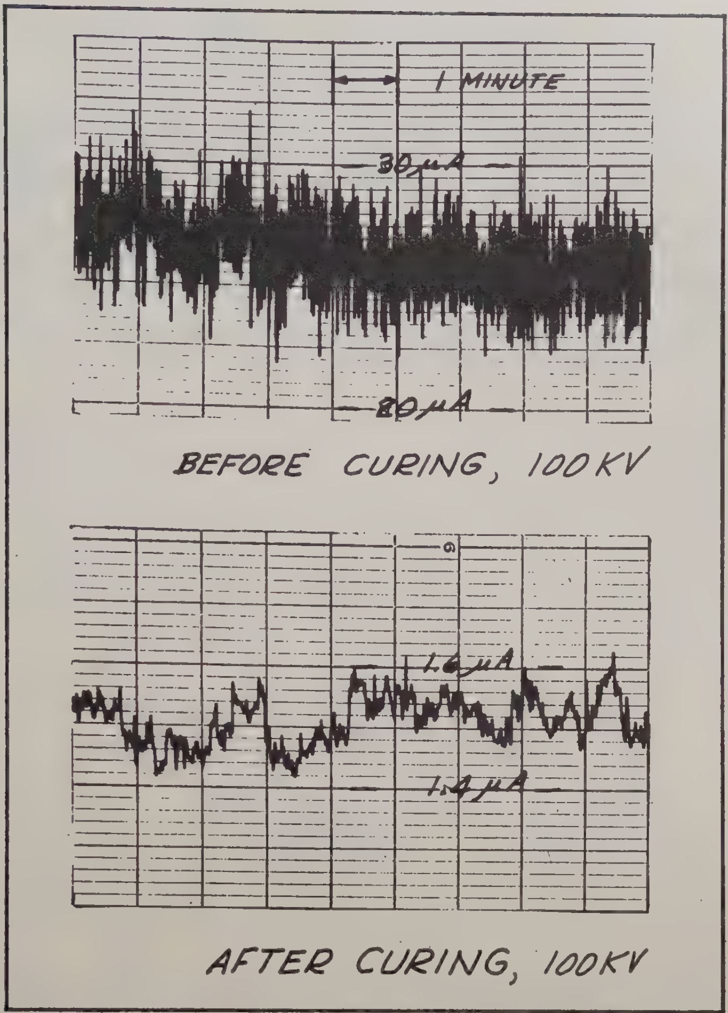

Fig. 3

Suppose it was decided to use an accelerated test, say, under higher temperature conditions. The cable would have been cured and an unsatisfactory item would have been passed. In this case, curing was necessary and we were equipped with a simple go-no-go kind of nondestructive test to accept or reject the vendors product without a risk of inadvertantly correcting a defect. This is not an isolated case. Component engineers in our activity were evaluating the validity of the hypothesis that each 8°C to 10°C increase in operating temperature reduced the life potential of a transformer by 50 per cent where Class A insulation was used. The beneficial effects of temperature curing were noted here also. Beneficial to the transformers, that is, and grossly misleading to one attempting to measure life by means of slowly applied step increase in temperature. This experience leads to selection of either one of two channels for future investigation. Because curing requires both time and temperature, one of these is essentially eliminated. In the case where no higher temperature is used than would be encountered in the equipment (or possibly a slightly higher value), voltage, vibration, cycling of temperature or cycling of load could be depended upon to obtain early failures. If it was desirable to minimize time as a factor, a thermal shock type of test could be used, such that curing is not realized before failures become substantial. The latter approach appears to be feasible, although

a decisive correlation with life remains to be established to our satisfaction. We have been conducting experiements in this field.

Another troublesome area involving the misleading effects of temperature arises in the use of solder. Most components use solder in some way. Capacitors, transformers, relays, some switches, potentiometers, etc., employ solder in critical places. But solder melts at about 170°C and we seldom, if ever, test at that temperature. However, let's examine the creep vs. time characteristic for solder in Fig. 4. This graph shows the elongation of a sample as a function of time at

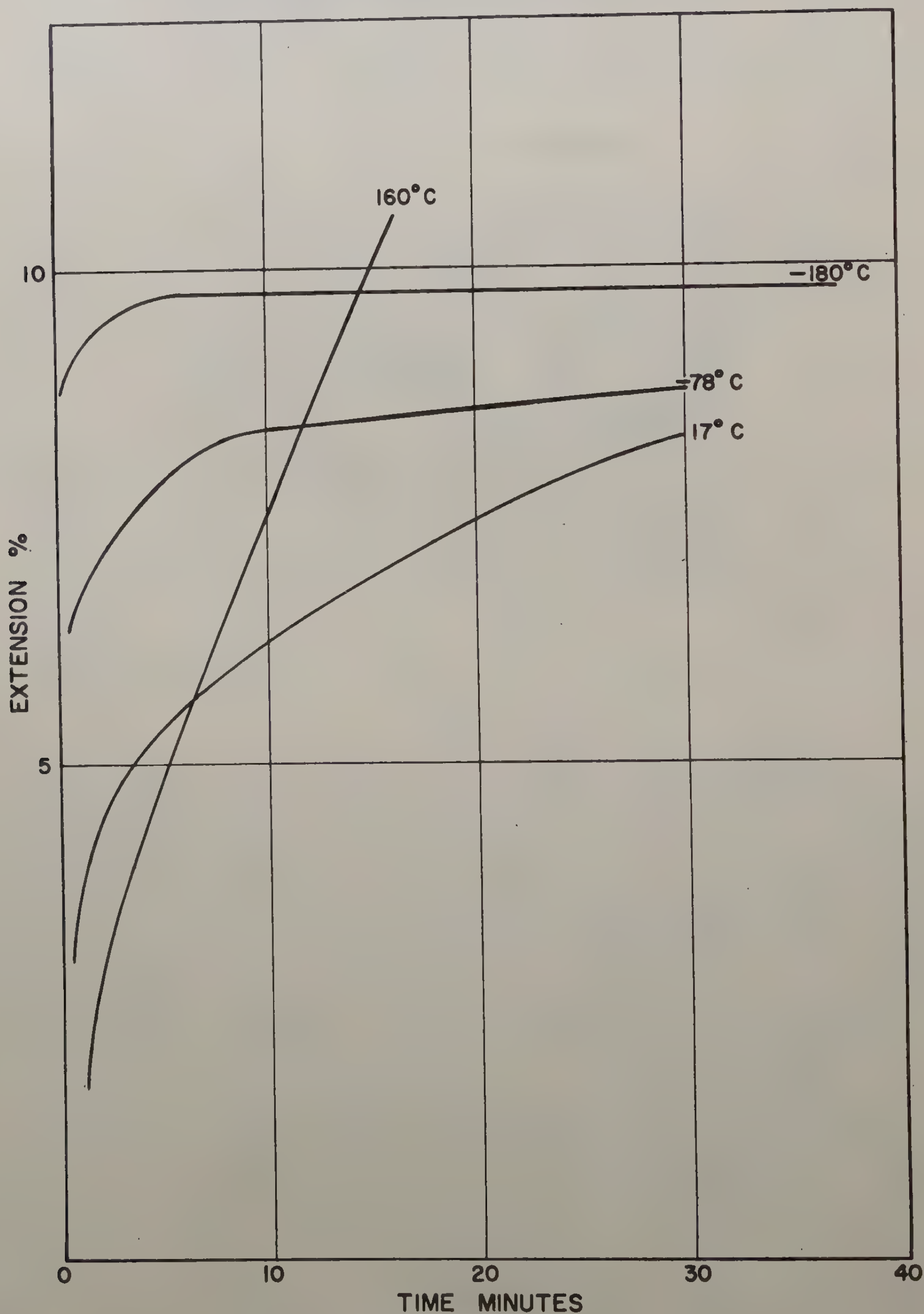

Fig. 4

a constant force. This elongation is accelerated at higher temperatures. In the region of 130°C to 150°C, solder becomes plastic and catastrophic failure will quickly result. This effect in a component may show up in one of two ways. A weakness in the component may be exposed, e.g., an application of solder where solder is in tension and is being depended upon for strength. Many feed-through terminals are designed this way. Testing at temperatures from 130°C to 150°C would expose these faulty applications of solder. On the other hand, a component during its manufacture may contain internal stresses that compromise its reliability. Failures may appear during vibration or hi-pot. Testing at 130°C to 150°C would, in many such instances, simply anneal the material and relieve the stresses, thereby permitting a bad component to be reported as good.

In studying accelerated testing as a means of measuring component failure rate without getting hopelessly involved in life-testing of thousands of samples, limitations such as these that we have experienced must be recognized and tests must be designed to avoid these pitfalls. There are limitations other than temperature, to be sure, but temperature seems to be misused most of all.

IN-PROCESS CONTROLS TO MAXIMIZE CAPACITOR RELIABILITY

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The building of reliability into capacitors in the manufacturing process should not be at all controversial. All users want this done. Military electronic applications demand it, and all reputable producers want to do it. Everyone agrees that reliability is not added by testing subsequent to manufacture.

However, a great deal of disagreement and confusion exists about how to estimate and improve reliability. It is common for both users and producers to maintain that a quantity of capacitors with a very low estimated process average will prove reliable in service. The estimate of process average may have been carefully calculated, but of what process average is it the estimate? By the user, it was probably calculated from receiving inspection records; by the producer, from final inspection records. If so, this estimate of process average will equal the number of units marked up "defective" because they were judged nonconforming to quality "standards," divided by units tested. These quality standards are generally built up over a period of time with engineering specifications and drawings as their foundation.

It is economical in practice to inspect only for the "headache" items, those that bring most frequent complaints from the production people who install the capacitors and from the quality control people who test the equipments. An example will illustrate the evolution of a typical item on inspection check lists. For years, rejections and complaints have been made for excess phenolic coating on the wire leads of phenolic-coated ceramic dielectric capacitors. The condition deserved the high place it was given on inspection check lists, because the user wanted to solder the wire lead where it was covered with an extension of the phenolic insulating coating which is applied to the capacitor body. This was usually reported as "poor workmanship" in quality reports and summaries. In the first place, of course, no workman touches the capacitors while they are at the coating operation. In the second place, the machinery was doing a good job; it had been designed so that not more than 5/32 in. of phenolic coating would extend onto the leads. Users began to solder closer to the capacitor body, and insulation on leads in excess of 1/8 in., then 1/16 in. and finally even 1/32 in. became objectionable. "Workmanship" was not involved. Process averages are weighted heavily with items such as this and, because they are mistakenly assumed to indicate poor workmanship, they are used as barometers of reliability.

What of electrical inspection test records? Those made by the user's receiving inspection section or the producer's final inspection section consist of capacitance, dielectric strength, case insulation and similar "times-zero" tests. Process averages do not usually include records of those few tests, such as the accelerated life test and sustained voltage test, which are good indicators of reliability. They are almost never used for process average computation, because the accuracy of a process average estimate is proportional to the number of units tested and relatively few units are given these tests. Even when accelerated life tests are regularly made, their results necessarily lag those of the

times zero tests, and it is not convenient to include them in the regular lot acceptance quality control reports.

Ordinarily, any correlation between process averages and reliability coefficients is purely accidental. In estimating reliability, the use of accelerated life test results of a few units would be preferable to using unrelated test results from millions of units. The nonsense which surrounds estimating the reliability coefficient of capacitors must be eliminated or efforts to achieve higher orders of reliability in their manufacture will be misdirected. It costs money to have engineers dig out and weigh facts, to take corrective action and to follow through. How those persons assigned to reliability improvement spend their time is important. Purchasing departments, only partially informed, can actually divert a producer's workers aiming for reliability from their goal. To have an effective program for developing a high reliability line, it is necessary to look to data from sources other than "times-zero" electrical tests, mechanical measurements and visual inspections.

Performance in service records and performance test records of capacitors under service conditions can, of course, provide the desired information. Because there is a scarcity of this information, few specifications mention the reliability coefficient they were written to assure. It is partly because "Reliability Assurance" is an inexact science that this Third National Symposium on Reliability and Quality Control in Electronics is being held.

A great deal of progress has been and is being made through the enlightened work and cooperation of users and producers. The high reliability development program at Erie was initiated with the study of several years of performance data, including information about the nature and causes of capacitor failure. This led to the establishment of the following guide posts.

1. All materials and designs included in the high reliability line must have a long, trouble-free history and inherent uniformity.

2. Capacitance ranges must be limited so that only heavier dielectrics with their resulting increased mechanical strength would be employed.

3. All design limits must be selected to assure generous safety margins.

4. Rigid in-process quality control must be maintained.

5. A proven failure theory must be used as the basis for establishing a 100 per cent reliability conditioning program.

In the initial studies it was found that the ceramic capacitor, because of its inherently good reliability, simplicity of design and excellent reproducibility, was ideally suited to high reliability development. The life test of ceramic dielectrics for a specified rate of failure varies approximately as the inverse of the cube of the voltage and halves for every 10°C rise in ambient temperature. This relationship can be written as follows:

$$L_2 = L_1\left(\frac{V_1}{V_2}\right)^3 .2^x$$

where L_1 = life time for a given percentage of failures under conditions of V_1 and T_1. (This is generally established by actual tests at a reasonably high voltage and temperature.)

L_2 = life time for the same percentage of failures as above but under conditions of V_2 and T_2.

V_1 and T_1 = voltage and temperature (°C) respectively under which the initial life time was established.

V_2 and T_2 = voltage and temperature (°C) respectively for which life time is desired.

$$X = \left(\frac{T_1 - T_2}{10}\right).$$

This expression is useful in estimating the life expectancy of a capacitor under a new condition of voltage and temperature when its life time under some standard test conditions that give a reasonably low percentage of failure is known. It cannot be used to estimate the life time for higher or lower percentages of failures than were experienced in the test at standard conditions unless the distributions of the failures is also known. This distribution is quite variable and can cover approximately one decade of time for ± 3 sigma.

Life curves for these capacitors show that the failures follow the normal distribution pattern quite well. For all practical purposes, they have no "wear out" under rated operating conditions. Therefore, the use of a sustained voltage load test which is not destructive is permitted. This will come in handy later in our reliability program. (See Page 46 of Engineering Bulletin 448-1 attached.)

Studies of failed specimens revealed:

1. More elaborate designs were less reliable than the standard ones. Molded styles were less reliable than the dip-coated ones, apparently because molding pressures against dielectrics sometimes caused them to fracture.

2. Generally speaking, both tubular and disc forms were most reliable when the dielectric thickness was not appreciably less than 0.020 in.

3. Capacitors which were silvered to maximum capacitance values were somewhat less reliable than those silvered below maximum.

4. Certain lots had abnormally high failure rates to which final inspection test data gave no clue. Lot history cards, however, did indicate that abnormal trouble had been experienced in processing the lot. Investigation in the line showed that, while the dielectric handling machinery when in good condition and adjustment operated without damage to dielectrics and maintained good insulating bands; when improperly adjusted or maintained it occasionally damaged or improperly silvered an appreciable portion of dielectrics in a lot before the malfunction was detected and corrected.

5. The accelerated life test data showed that more than 99 per cent of our standard ceramic capacitors live quite long. In fact, since they will

live considerably longer than their companion components, it can be said that they will probably outlive their usefulness. The evident solution was to prevent the manufacture of the remaining less than 1 per cent incipient failures or to devise a method for their detection and removal after manufacturing.

Frequency distributions of failure causes were made from failed specimen analyses. These formed the basis of a priority list for corrective measures to be taken in the manufacturing processes. A comprehensive quality control system had already been installed and was functioning well, so there was a minimum of trouble in getting team efforts from production, engineering and quality control people applied to the tasks. The corrective actions taken and controls established in connection with the high reliability program are too numerous to mention; the following are illustrative.

1. Sources of contamination in the ceramic formulations were reduced in number, and the degree to which the few remaining ones contributed was minimized by more effective filtering and separation.

2. Other flaws found to contribute to failure incipiency and which are visible in dielectrics were given emphasis on inspection check lists. Substandard material "deviations" were made taboo for use in high reliability lines.

3. As mentioned above, dielectric handling machinery when worn or poorly set was an important source of trouble. Good quality control inspection techniques were already in use. A weakness was found to be that in the fifteen minute interval between the start of a new lot run and the first check by the process inspector, flaws could be introduced into a considerable number of capacitor elements. A rigid setup check was introduced which required proper adjustments to the chucking, silver application and other devices before the machines were permitted to operate. Setup pieces were scrapped. Preventive maintainence schedules were pulled up so that parts of machines found to cause incipient failures when worn were replaced long before this danger could arise.

4. All high reliability units receive extra inspections and checks throughout processing. They are specially marked and their lot history cards contain special precautions. All of these record cards are kept on file after the capacitors have been shipped. Since each of those concerned has been kept fully informed of the objectives of the high reliability program, slight irregularities of the sort which cannot be anticipated are quickly reported and evaluated.

At this point in the program's development, Erie first began to market a high reliability line. A specification was set up for these capacitors which provided the controls mentioned above and others. It also stipulated that "performance tests" be made on a sample drawn from each shipment. Among these tests was a 250 hour accelerated life test with twice rated working voltage (1,000 VDC) applied in 85°C ambient temperature. Results are shown below.

Number of lots samples	137
Number of units tested	3,288
Number of failures (insulation resistance $<$ 1,000 MegΩ)	2

These results look good when it is recalled that the life time varies approximately as the inverse of the cube of the voltage. The two units would probably have lasted a great deal longer if they had been tested at rated voltage (500 VDC). However, this is not by any means certain, because they were obviously "strays."

Corrective actions and preventive controls such as the above-mentioned served to minimize the production of incipient failures. However, since reliability coefficients of the order of 99.99 per cent and even 99.999 per cent were desired, a tool had to be found which could detect the few remaining finished capacitors with latent flaws of the kind known to cause early failures. As mentioned earlier, the inherently long life of good ceramic capacitors permits them to be subjected to sustained voltage loads without appreciable shortening of their life. This fact was utilized to provide the basic part of "reliability assurance sorting" tests applied to finished capacitors in the high reliability lines. It consists essentially of submission to 1,250 VDC sustained for 24 hours. The combined failure rates of this test and subsequent dielectric strength and insulation resistance tests is limited to less than 1 per cent for the lot to pass with no further screening. If the combined failures equal between 1 per cent and 4 per cent, the lot may be tested once more with acceptance at a combined failure rate of less than 1 per cent on the second test. A combined failure rate of 4 per cent or more on the first test sequence fails the lot.

The program outlined has upgraded reliability. We do not know the probability that a capacitor so manufactured and conditioned will survive 1,000 hours under rated conditions. While extrapolations can be made from accelerated life tests concerning life time, such extrapolations are perhaps not valid in estimating failure rates under rated conditions. Estimates of reliability coefficients can probably only be made from large quantities of tests made under rated conditions. Since these tests are much less severe, they would run for much longer periods of time. Although many new test panels have been constructed, they are filled up with accelerated life tests and reliability assurance sorting tests. A "rated condition" testing program is now planned, however, to provide the needed data.

Erie's specification #900 as developed for High Reliability Ceramicon capacitors, Level 1, is found on pages 49 through 53 in the attached Engineering Bulletin 448-1. Erie also has a high reliability program in effect for Button Style Silvered-Mica capacitors which has been similar in its approach. This has not been outlined here only because it was felt that ceramic capacitors were of more general interest.

* * *

ERIE electronics

ENGINEERING BULLETIN

OCTOBER, 1956 BULLETIN NO. 448-1

HI-RELIABILITY CERAMICONS

Level 1 *

Because of increasing demands for very high orders of equipment reliability in the field of electronic business machines and military electronic devices, Erie Resistor Corporation has developed a Hi-Reliability line of ceramic capacitors. The HR Ceramicon is the result of several years of research and engineering study into the nature of capacitor failures.

The ceramic capacitor, because of its inherently good reliability, simplicity of design and excellent reproducibility, is ideally suited to high reliability development. On this basis Erie undertook such a development program and, in active cooperation with several equipment manufacturers, has successfully produced HR Ceramicons, which exhibit degrees of reliability not considered feasible a few years ago.

The Erie HR development program is largely based on Erie's many years of experience in the successful manufacture of Ceramicons. During this period a vast store of information concerning the nature and cause of capacitor failures has been accumulated. Using this data for information, the following guideposts were set for the Erie HR Ceramicon development:

1. All materials and styles included in the HR line had a long, trouble-free history and inherently good process capabilities.

2. Capacitance ranges were limited so that only the heavier dielectrics, with their resulting increased mechanical strength, would be employed.

3. All design limits were selected to assure generous safety margins.

4. Rigid in-process quality control was established.

5. A proven failure theory was used as the basis for establishing a 100 per cent reliability conditioning program. All HR capacitors are subjected to this program prior to shipping in order to detect and remove any possible defectives.

All Erie HR Ceramicons exceed the requirements of the corresponding government specifications (JAN-C-20A, or MIL-C-11015A, as applicable).

*Level 1 refers specifically to Erie Specification #900.

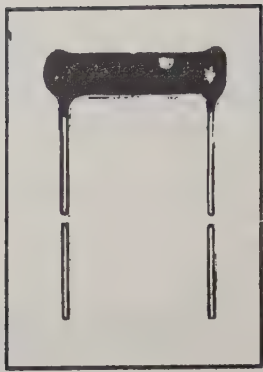


Fig. 1

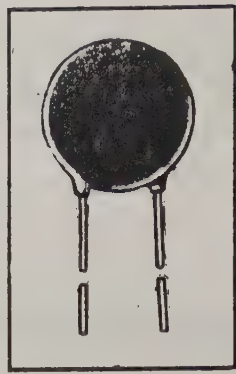


Fig. 2

ERIE HR TUBULAR CERAMICONS

The Erie HR Tubular Ceramicon (Fig. 1) is a small, fixed capacitor consisting essentially of a tubular ceramic dielectric on which silver electrodes are fused at a very high temperature. By varying the composition of the dielectric material, various temperature coefficients and dielectric constants may be obtained. The lead wires are copper with a heavy solder coating to provide ease of soldering and permit long storage without degradation of solderability. The leads are securely wrapped in a manner enabling them to withstand severe axial mechanical stresses. The entire dielectric is coated with a thermosetting phenolic material which is in turn vacuum wax impregnated to provide further moisture protestion.

To assure the very highest order of reliability in service, very heavy safety factors have been designed into HR Tubulars. The standard marking method for Tubulars includes a silver HR identification dot located on the under side of the tube. In addition, the standard RETMA 5 dot color code is applied for easy identification on Types I and II, and a 6 dot color code is used on Type III.

ERIE HR DISC CERAMICONS

The Erie HR Disc Ceramicon (Fig. 2) is basically the same as the tubular type, except that the dielectric is in the form of a disc rather than a tube. The electrodes are circular patterns centered on opposite sides of the disc and fused intimately to the dielectric at a very high temperature. The heavily tinned copper-wire leads are firmly soldered to the electrodes. The entire unit is coated with thermosetting phenolic material, which is further protected from moisture by vacuum wax impregnation.

Standard marking for HR Disc Ceramicons includes the Erie trade mark, the symbol "HR," the nominal T.C., the capacitance and tolerance. Where space does not permit all of the preceding information, the trade mark and capacitance tolerance will be omitted.

STANDARD PROCEDURE FOR ORDERING HR CERAMICONS

As indicated in Figs. 3 and 4, Erie HR Ceramicons are available in two tubular (HR 341 and HR 342) and five disc (HR 839, HR 809, HR 819, HR 849 and

HR 829) styles, each having a wide range of capacitance values and temperature characteristics. To order any of these styles, specify the following in the sequence of steps shown here, and refer to the figures indicated in the example below.

1. Capacitor style (HR 341, HR 809, etc.)

2. Nominal temperature coefficient or letter characteristic (P100, N750, Characteristic X5F, etc.) See Figs. 3 and 4.

3. Temperature coefficient tolerance (±30p/m/°C, ±60p/m/°C, ±120p/m/°C, etc.) This is omitted where a letter characteristic is indicated in step 2 above.

4. Nominal capacitance value in mmf.

5. Capacitance tolerance.

Example 1

The unit is to be tubular in type with a nominal temperature coefficient of -750 parts/million/°C in a capacitance of 82 mmf with a ±5 per cent tolerance. The type number for ordering is therefore:

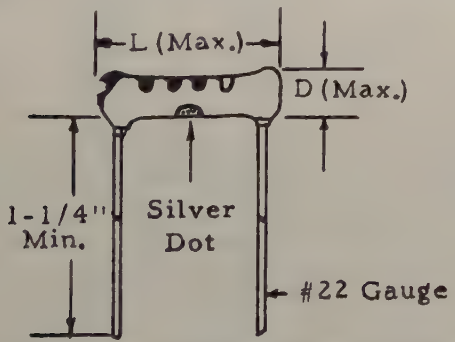
HR 342 -- See step 1 above, and see Fig. 3 for the style required to meet capacitance and TC.

N750 -- See step 2 and Fig. 3.

±120 -- See step 3 and Table IV.

82 mmf -- See step 4 and Fig. 3.

±5 per cent -- See step 5 and Table I.



HR Style	L	D
HR 341	.460	.240
HR 342	.710	.240

Temp. Char.	P100	NPO	N030	N080	N150	N220	N330	N470	N750	See Pages 9 & 10			
										SL	X5F	X5T	X5V
HR 341	.75-8.2	.75-15	.75-15	1.0-18	1.0-20	1.0-22	1.0-25	1.0-31	1.5-43	.75-43	44-560	561-860	861-1500
HR 342	8.3-20	16-39	16-39	19-47	21-51	23-56	26-62	32-75	44-100	44-100	561-1300	1301-2200	2201-4400

Fig. 3 - Capacity range in mmf.

Example 2

The unit is to be a disc type construction with a "G" temperature characteristic, a nominal capacitance of 2,200 mmf and a capacitance tolerance of ±20 per cent. The type number for ordering is therefore:

HR 819 -- See step 1 above, and see Fig. 4 for the style required to meet capacitance and characteristic requirements.

Characteristic X5T -- See step 2 and Fig. 4.

2,200 mmf -- See step 4 and Fig. 4.

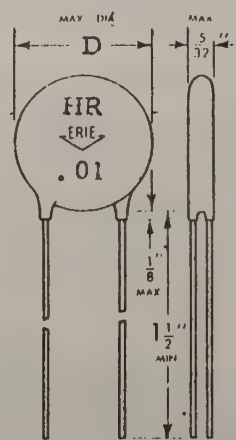
±20 per cent -- See step 5 and Fig. 4.

TEMPERATURE CHARACTERISTICS

Temperature Compensating -- Type I (P100 through N750)

Erie HR Tubular and Disc Ceramicons are capacity-sensitive to temperature in varying, predetermined degrees. Because of this characteristic, they have found widespread application as temperature compensating elements in circuits which must be frequency-stabilized over wide temperature ranges. They are also manu-

HR Style	D
HR 839	5/16
HR 809	3/8
HR 819	19/32
HR 849	11/16
HR 829	3/4



Temp. Char.	P100	NPO	N030	N080	N150	N220	N330	N470	N750	See Pages 9 & 10			
										SL	X5F	X5T	X5V
HR 839	2-6	3-11	3-12	3.5-13	4-15	4.5-16	5-18	6-22	7-30	2-30	31-430	431-560	561-1000
HR 809	7-9	12-18	13-19	14-22	16-25	17-27	19-30	23-36	31-50	31-50	431-710	711-1000	1001-1700
HR 819	10-25	19-47	20-49	23-57	26-65	28-72	31-80	37-96	51-130	51-130	711-2000	2001-2700	2001-4700
HR 849	26-39	48-70	50-73	58-86	66-100	73-110	81-120	97-150	131-200	131-200	2001-2400	2701-3900	4701-8200
HR 829	40-48	71-91	74-94	87-110	101-123	111-135	121-150	151-180	201-250	201-250	2401-3900	3901-5000	8201-10000

Fig. 4 - Capacity ranges in mmf.

TABLE I

Available Capacity Tolerances for HR Tubular Ceramicons

Capacity	Types I & II P100 through N750 and SL	Type III X5F	X5T	X5V
0.75-100 mmf	±0.1 mmf, ±0.25 mmf ±0.5 mmf, ±1 mmf* ±2 mmf*	Not available	Not available	Not available
11-100 mmf	1%, 2%, 5% 10% 20%	(±10%, ±20%)	Not available	Not available
101-4,400 mmf	Not available above 100 mmf	(±10%, ±20%)	±10% ±20%	+ 50%, - 20% + 80%, - 20% + 100%, - 0% + 100%, - 20% GMV†, ± 20%

*Applicable only if nominal exceeds tolerance.
†Guaranteed minimum value.

TABLE II

Available Capacity Tolerances for HR Disc Ceramicons

Capacity	Types I & II P100 through N750 and SL	Type III X5F	X5T	X5V
2-4.3 mmf	±1 mmf ±2 mmf	Not available	Not available	Not available
4.4-10 mmf	±0.25 mmf, ±0.5 mmf ±1 mmf, ±2 mmf	Not available	Not available	Not available
11-30 mmf	±2.5%, ± 5% ± 10%, ±20%	Not available	Not available	Not available
31-90 mmf	±2.5%, ± 5% ± 10%, ±20%	±10% ±20%	Not available	Not available
91-250 mmf	±5% ±10% ±20%	±10% ±20%	±10% ±20%	+ 80, - 20% + 100, - 0% + 100, - 20% GMV
251-10,000 mmf	Not available	±10% ±20% Not available above 2,000 mmf	±10% ±20% Not available above 4,700 mmf	+ 80, - 20% + 100, - 0% GMV Not available below 560 mmf

factured with practically no thermal sensitivity for use in applications requiring a capacitor whose value is not affected by temperature.

Like all temperature-sensitive materials, the temperature characteristic of Erie HR Ceramicons is not linear; i.e., the capacity does not change uniformly as the temperature changes. The manner in which the capacity changes with temperature, however, has been the subject of study at Erie Resistor for a number of years and is accurately known. This information is shown in Fig. 5.

P100 Ceramicons have a nominal positive temperature coefficient of capacity of 100 parts/million/ °C. The N750 units have a negative coefficient of 750

TABLE III

Summary of Initial Characteristics for HR Discs and Tubulars

Initial characteristics	Types I & II P100 through N750 and SL	Type III X5F	Type III X5T	Type III X5V
Measurement frequency for capacitance and power factor	1 mc	1 kc	1 kc	1 kc
Maximum power factor	0.1% above 30 mmf. See par. 2.1 (b) of specifications for lower values.	1.5%	2.0%	2.0%
Rated dc working voltage	500 v	500 v	500 v	500 v
Maximum temperature at rated voltage	+85°C	+85°C	+85°C	+85°C
Minimum Insulation resistance, megohms at 25°C	100,000	50,000	50,000	50,000
Dielectric strength test	2,000 v	2,000 v	2,000 v	2,000 v
Temperature characteristic	Within ±30 parts/million/°C or ±20% of nominal TC, whichever is greater for values of 10 mmf and above. See Table IV for lower values.	Maximum capacity change from 25°C value is ±10% from -55°C to + 85°C.	Maximum capacity change from 25°C value is + 22% - 33% from - 55°C to + 85°C.	Maximum capacity change from 25°C value is + 22% + 75% from - 55°C to + 85°C.
TC Color Code		Gold, red	Gold, green	Gold, violet

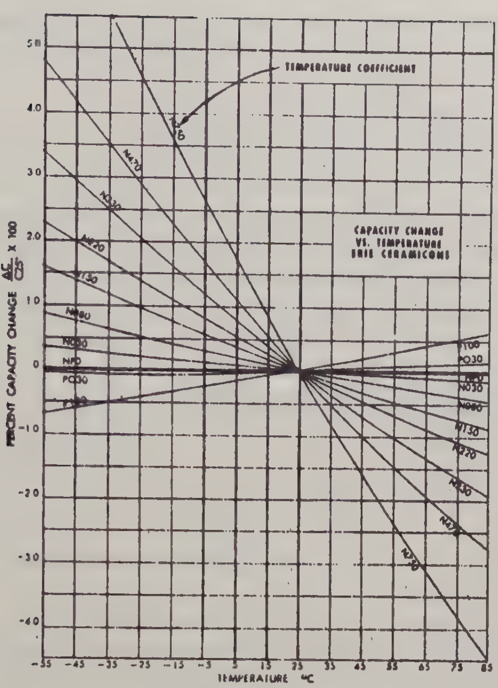


Fig. 5 - Temperature Compensating HR Ceramicons.

parts/million/ °C. These values correspond to a rise of 0.6 per cent and a drop of 4.5 per cent, respectively, as the temperature is raised ~~from~~ + 25°C to + 85°C. Intermediate values are available as shown in Figs. 3 and 4. Commercial tolerance on temperature coefficient (as determined by measurement at 25°C and 85°C) is shown in Table IV.

The Q factor of Erie HR Temperature Compensating Ceramicons will decrease slightly as the temperature increases. In general, the decrease in Q factor at

TABLE IV

Nominal temperature coefficient	Tolerance in P/M/°C on Temperature Coefficient as Determined by Measurement at 25°C and 85°C			
	Capacity 0.5 to 2 MMF	Capacity 2.1 to 3.9 MMF	Capacity 4 to 9.9 MMF	Capacity 10 MMF and Over
P100	±250	±120	± 60	± 30
P030	±250	±120	± 60	± 30
NPO	±250	±120	± 60	± 30
N030	±250	±120	± 60	± 30
N080	±250	±120	± 60	± 30
N150	±250	±120	± 60	± 30
N220	±250	±120	± 60	± 30
N330	±200	±120	± 60	± 60
N470	±250	±120	±120	± 60
N750	±250	±120	±120	±120

elevated temperatures up to 85°C will not exceed 0.5 per cent of the Q factor at 25°C for each degree rise.

General Purpose -- Type II (Characteristic SL)

General Purpose Type II HR Ceramicons are identical to the Temperature Compensating Type I units previously described, except that the temperature coefficient is less restricted, thus permitting a wider selection of dielectrics in manufacture. In all cases, the coefficient is limited to N330 ±500 ppm/°C. At any temperature between -55°C and +85°C, the capacity change, referred to the +25°C reading, will not exceed the shaded area in Fig. 6 below.

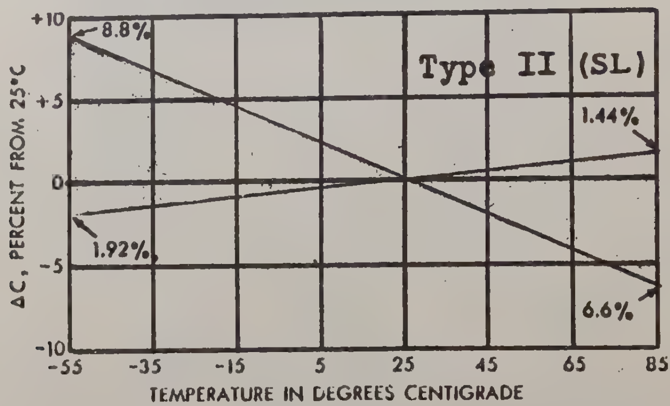


Fig. 6

General Purpose -- Type III (Characteristics X5F, X5T and X5V)

General Purpose Type III HR Ceramicons, available in values from 31 mmf to 10,000 mmf, utilize the Erie Hi-K dielectrics. Three temperature characteristics, X5F, X5T and X5V, are employed with the limiting characteristics outlined in paragraph 3.2 of Erie Specification #900. Typical temperature characteristic curves are shown in Figs. 7 and 8.

LIFE CHARACTERISTICS OF ERIE HR CERAMICONS

The matter of rated working voltage is one which must be carefully considered and defined in the case of high-reliability applications. The working voltages listed in Table III (500 v in all cases) are based on the general ability of the parts to withstand 1,000 VDC applied continuously for a minimum of 1,000 hours at a temperature of + 85°C. This rating is based on a long standing industry standard, but must be understood as arbitrary in nature. Since there is a wide range of temperatures, voltages and estimated life times, it is desirable to have an expression enabling the design engineer to determine what life time he may expect from the component. Such an expression, based on experimental data, is developed below and should be used to evaluate these capacitors under actual operating conditions.

The data shown in Fig. 9 is typical for HR Ceramicons when operated at extremely high temperatures. The points shown represent failures in a regular production lot. One hundred pieces were placed on a "test to destruction" life test at + 150°C at 600 v and 900 v continuous dc (a total of 200 pieces).

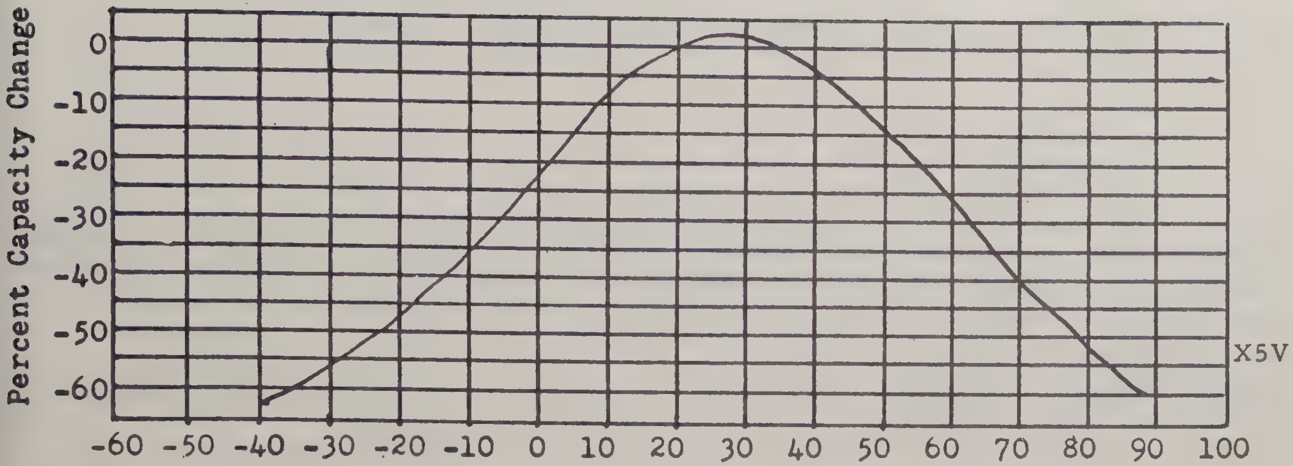


Fig. 7

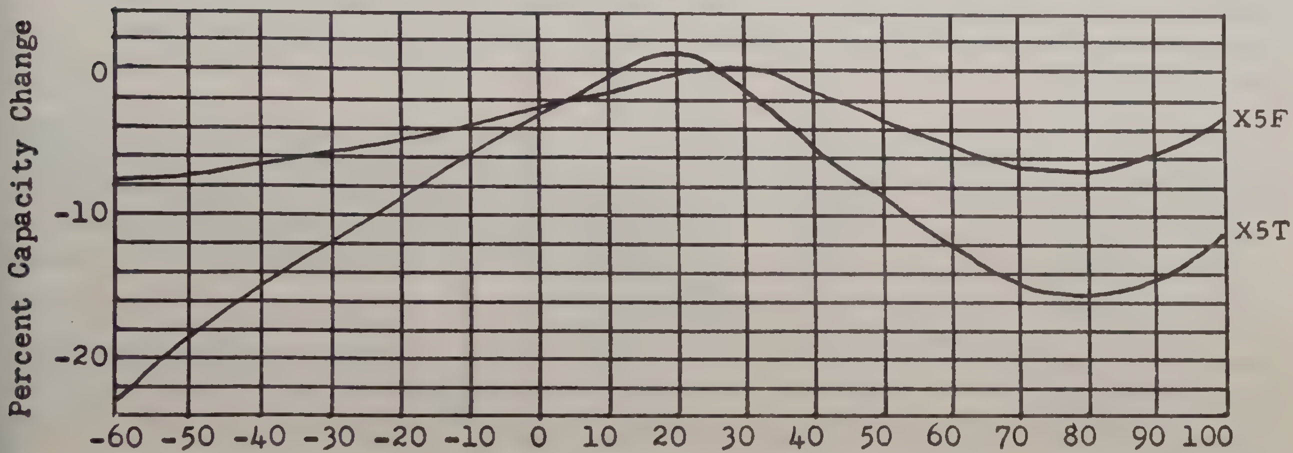


Fig. 8

The life time of ceramic dielectrics for a specified rate of failure varies approximately as the inverse of the cube of the voltage and halves for every 10°C rise in ambient temperature. This relationship can be written as follows:

$$L_2 = L_1\left(\frac{V_1}{V_2}\right)^3 .2^x$$

where L_1 = Life time for a given percentage of failures under conditions of V_1 and T_1. (This is generally established by actual tests at a reasonably high voltage and temperature.)

L_2 = Life time for the same percentage of failures as above, but under conditions of V_2 and T_2

V_1 and T_1 = Voltage and temperature (°C) respectively under which the initial life time was established

V_2 and T_2 = Voltage and temperature (°C) respectively for which life time is desired

$$X = \frac{T_1 - T_2}{10} .$$

This expression is useful in estimating the life expectancy of a capacitor under a new condition of voltage and temperature when its life time under some standard test conditions that give a reasonably low percentage of failure is known. It cannot be used to estimate the life time for higher or lower percentages of failures than was experienced in the test at standard conditions unless the distributions of the failures is also known. This distribution is quite variable and can cover approximately one decade of time for ±3 sigma.

It should be pointed out that a great deal of additional research is required before definite life time limits can be established. This work is being performed on a continuing basis here at Erie Resistor Corporation. We believe the Hi-Reliability Ceramicon is a great step forward in the field of reliability and trust it will prove to be a valuable component for the design engineer.

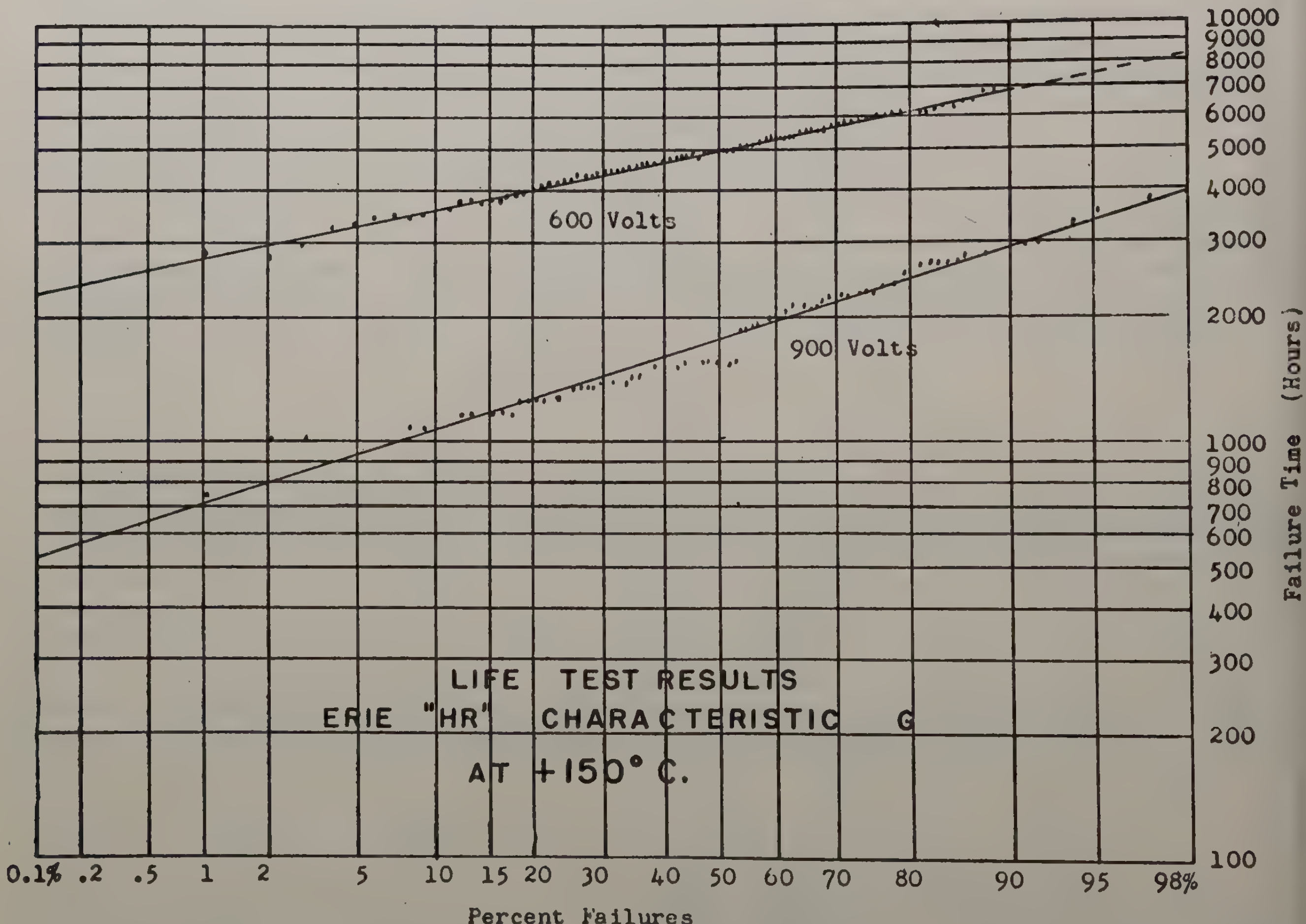


Fig. 9

ERIE SPECIFICATION #900

1. Scope

This specification for HR Ceramicon Capacitors includes the performance requirements for ceramic dielectric capacitors of the temperature compensating and Hi-K types. It provides for capacitors having, when operated within their ratings, a very high order of reliability. Types of capacitors covered by this specification and the applicable test paragraphs are as follows:

Type of Capacitor	Qualification Test Paragraph	Production Test Paragraph
Type I - Temperature compensating capacitors intended for use in temperature correcting or temperature stable circuits and having a nominal temperature coefficient in the range of + 100 ppm/ °C to - 750 ppm/ °C inclusive. The nominal temperature coefficient tolerance does not exceed ±250 ppm/ °C. (See Fig. 5.)	2	4
Type II - General Purpose Capacitors using dielectrics having any TC between + 100 and - 750 ppm/ °C. This category has a nominal T. C. of N330 ±500 ppm/ °C.	2	4
Type III - General Purpose Capacitors having dielectric constants between 100 and 3,500 and having variable temperature coefficients.	3	4

2. Qualification Requirements for Type I and Type II Capacitors

Unless otherwise specified, all tests are performed at, or referred to an ambient temperature of 25°C and a relative humidity not greater than 50 per cent. Complete qualification tests are to be performed on 25 pieces of the highest capacitance value of each style covered by this specification. One failure is permitted in each test. The tests are to be repeated on a continuing basis as frequently as is practical.

2.1 Initial Tests - This series of electrical tests shall be performed in the order shown.

(a) Capacitance - Capacitance shall be within the limits specified on the purchase order and its associated specifications when measured at a frequency of 1 mc using a Q meter or equivalent.

(b) Q - When measured at a frequency of 1 mc, with an RMS voltage no greater than 5 volts, the Q shall be greater than 1,000 for all values of 30 mmf and above. For values less than 30 mmf, the minimum Q is given by the expression 20 (C + 20) where C is the capacitance in mmf.

(c) Insulation resistance shall exceed 100,000 megohms when measured at 100 volts dc with a one-minute maximum electrification time. Voltage is applied through a protective resistor which limits the surge current to 50 ma.

(d) Dielectric strength - Capacitors shall be capable of withstanding a dielectric strength test of 2,000 volts dc for a period of 5 seconds. Voltage is applied through a protective resistor which limits the surge current to 50 ma.

(e) Dielectric strength of body insulation shall be such as to withstand a direct potential of 2.5 times rated dc working voltage for one second. This test is to be performed by submerging the body of the capacitor in a container of #9 shot to within 1/16 in. of the point of lead egress. The voltage is applied between the two leads connected together and the shot. Voltage is applied through a resistor which limits the surge current to 50 ma.

2.2 Temperature coefficient - On the basis of a two-point measurement at + 25°C and - 85°C, the temperature coefficient shall be within the limits specified on the purchase order and its associated specifications. Limits at temperatures below 25°C will be supplied on request and in all cases will be within the limits outlined in JAN-C-20A.

2.3 Capacitance drift - The capacitor shall be subjected to the following temperature cycle: + 25°C, - 55°C, + 25°C, + 85°C and + 25°C. The capacitance shall be measured at each of the + 25°C points at a frequency of 1 megacycle. The capacitance drift shall not exceed 0.2 per cent or 0.05 mmf, whichever is greater, as determined by the greatest difference between any two of the three 25°C readings. Each measurement shall be made after the capacitor has reached thermal stability.

2.4 Temperature and immersion cycling - Capacitors shall be exposed to five consecutive temperature cycles as follows: + 25°C, - 55°C, + 25°C, + 85°C and + 25°C. The rate of temperature change shall not be less than 2°C per minute and the units shall be held at the extreme temperatures for at least 30 minutes. The temperature cycling shall be followed by two cycles of 15 minute immersions in saturated solutions of sodium chloride and water; one at + 65°C, + 10, - 0°C; and the other at + 20°C, + 0, - 10°C. Capacitors shall then be washed in clear water and surface moisture shall be removed by circulating air and/or by wiping with a clean, dry cloth. After a drying period not to exceed 24 hours at standard test conditions, the Q shall be at least 50 per cent of the value specified in paragraph 2.1 (b) and the insulation resistance shall exceed 50,000 megohms when measured as described in paragraph 2.1 (c).

2.5 Temperature cycling and humidity - Capacitors shall be exposed to five consecutive temperature cycles as outlined in paragraph 2.4. The temperature cycling shall be followed by a continuous exposure of 100 hours at a temperature of 40°C and a relative humidity of 90 per cent to 95 per cent. Following these exposures by not less than 30 minutes, the following tests shall be performed in the order given:

(a) Capacitance change shall be measured as specified in 2.1 (a). The capacitance change shall not exceed 2 per cent.

(b) Q - Q of the capacitor, as measured in 2.1 (b) shall not be less than 350 for units of 30 mmf or above. Between 10 mmf and 30 mmf, the minimum Q is given by the expression 2.5 (C + 110). Below 10 mmf, the minimum Q is given by the expression 10 (C + 20).

(c) Insulation resistance shall exceed 50,000 megohms when measured as in 2.1 (c).

2.6 Life Test - After accurately measuring capacitance as specified in 2.1 (a), the capacitor shall be subjected to a dc test voltage two times the rated dc voltage of the capacitor for a period of 1,000 hours at a temperature of 85 ±3°C. After this test, the capacitor shall meet the following specifications in the order given:

(a) Capacitance change shall be measured as in 2.1 (a). Capacitance change shall not exceed 2 per cent or 0.5 mmf, whichever is greater.

(b) Q - Q of the capacitor shall be as specified in 2.5 (b).

(c) Insulation resistance shall exceed 50,000 megohms when measured as in 2.1 (c).

3. Qualification Requirements for Type III Capacitors

Unless otherwise specified, all tests are performed at, or referred to, an ambient temperature of 25°C and a relative humidity not greater than 50 per cent.

3.1 Initial Tests - This series of electrical tests shall be performed in the order shown:

(a) Capacitance shall be within the limits specified on the purchase order and its associated specifications when measured at a frequency of 1 kc with 1.0 ±.5 v rms applied.

(b) Power factor when measured as outlined in 3.1 (a) shall not exceed 2.0 per cent.

(c) Insulation resistance shall exceed 50,000 megohms when measured at 100 VDC with a one-minute electrification time.

(d) Capacitors shall be capable of withstanding a dielectric strength test of 2,000 VDC for a period of 5 seconds.

(e) Dielectric strength test of body insulation shall meet the requirements outlined in paragraph 2.1 (e).

3.2 Temperature Characteristic - Capacitance change shall not exceed the limits specified in Table V when determined by a single run from - 55°C to + 85°C. Capacitance measurements shall be made at a frequency of 1 kc with 1.0 ±0.5 v rms applied. Each measurement shall be made after the capacitor has reached thermal stability.

TABLE V

Limits of Capacitance Change With Temperature
(Type III Capacitors)

Temperature Characteristic	Limits of Capacitance Change Referred to Initial Measurement of + 25°C
X5F	+ 10% to - 10%
X5T	+ 22% to - 33%
X5V	+ 22% to - 75%

3.3 Temperature and immersion cycling - Capacitors shall be exposed to the temperature and immersion cycling as outlined in paragraph 2.4. After the drying period, the power factor shall not exceed 3.0 per cent measured at 1.0 ±0. 5 v rms at a frequency of 1 kc; the insulation resistance shall be at least 20,000 megohms when measured as in paragraph 3.1 (c); and the units shall meet the dielectric strength requirement of paragraph 3.1 (d).

3.4 Temperature cycling and humidity - Capacitors shall be exposed to temperature cycling and humidity as outlined in paragraph 2.5. Following the humidity test by not less than 30 minutes, the power factor, insulation resistance and dielectric strength shall be measured as specified in paragraphs 3.1 (b), 3.1 (c) and 3.1 (d) respectively. The power factor shall not exceed 3.0 per cent; the insulation resistance shall exceed 10,000 megohms; and the units shall withstand the dielectric strength requirements of paragraph 3.1 (d).

3.5 Life Test - Capacitors shall be subjected to the life test specified in paragraph 2.6. After life test, the power factor shall not exceed 3 per cent when measured as described in paragraph 3.1 (b) and the insulation resistance shall be no less than 10,000 megohms when measured as outlined in paragraph 3.1 (c).

4. Production Testing Requirements of Types I, II and III Capacitors

4.1 Production Sampling Tests

(a) Workmanship - Sampled in accordance with MIL-STD-105 procedure, the acceptable quality level shall be 1.5 per cent for visual and mechanical defects.

(b) Temperature Characteristic - Each lot of ceramic dielectrics used in the manufacture of HR Ceramicons shall be sampled and tested for conformance to the specified temperature characteristic limits prior to assembly.

(c) Dielectric Strength of Body Insulation - Sampled in accordance with MIL-STD-105 procedure and tested as outlined in paragraph 2.1 (e), the acceptable quality level shall be 0.65 per cent.

4.2 Reliability Assurance Sorting

(a) Dielectric Strength Test - All units (100 per cent of each lot) are to be tested by application of a dc voltage of 2,000 VDC for a period of 2 seconds. All units failing to withstand this voltage are to be removed from the lot.

(b) Life Test - After testing as in paragraph 4.2 (a) and 4.2 (b) above, all units (100 per cent of those not previously removed from the lot) shall be tested for a continuous 24 hour period at 1,250 VDC and at a temperature of 25°C ±3°C. All units which fail under these conditions are to be removed from the lot.

(c) Dielectric Strength Test - All units which successfully pass the tests of paragraph 4.2 (a) and 4.2 (c) are to be tested again as outlined in paragraph 4.2 (a). All defective units are to be removed.

(d) Insulation Resistance - All units (100 per cent of each lot) shall be tested to the limits outlined in paragraph 2.1 (c) (for Types I and II) or paragraph 3.1 (c) (for Type III). All units failing to meet the applicable limits are removed from the lot.

(e) If the accumulated failures in the life test [paragraph 4.2 (b)], the subsequent dielectric strength test [paragraph 4.2 (c)] and the subsequent insulation resistance test [paragraph 4.2 (d)] are less than 1 per cent of the lot, the lot shall be considered acceptable. If the accumulated failures are between 1 per cent and 4 per cent of the lot, the lot may be retested once and will be considered acceptable if less than 1 per cent fail on the second test. If 4 per cent or more of the lot fail on the first test, the lot will be rejected.

(f) Capacitance and Q Test - All lots which successfully pass the above reliability tests will be 100 per cent tested and sorted for conformance to the capacitance and power factor requirements outlined in paragraph 2.1 (a) and 2.1 (b) (for Types I and II) or paragraphs 3.1 (a) and 3.1 (b) (for Type III). All units not meeting these requirements are removed from the lot before shipment.

MILITARY WEAPON SYSTEMS COMPLEX AND THE PROFESSOR FACTOR

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I was in a quandary about the line of approach to take in this paper; in fact, I think I was in two quandaries. I had selected a title which even I didn't understand, but I hoped it would be sufficiently confusing to enable me to develop the subject matter without concerning myself about the confining influences of a title. My quandary continued in a healthy state until a most extraordinary opportunity, which settled the matter for me, offered itself during one of my visits to Washington.

Sometime last October (or maybe it was November) I was in the Pentagon Building, wandering about from gon to gon, and I found myself approaching an executive dining room. When I was about a hundred yards away, it became evident that the Army, Navy and Air Force were engaged in a high-level, friendly discussion about missile jurisdiction. I could hear dignified and subdued screams and yells, and as I approached it became obvious that the Army and the Air Force had narrowed down the discussion to the intercontinental missile. I couldn't hear everything that was said because of a persistent rumbling and the disconcerting vibration of the structure in the general area. There was apparently some from of natural phenomenon, possibly an earthquake, producing these annoying perturbations, and it interfered with my fully understanding the discussion under way. I gathered, however, that the Air Force and the Army were each trying to yield jurisdiction of the intercontinental missile to the other. I think General Alphonse, of the Air Force, was suggesting that the Army was much better equipped to handle a project of such proportions and, therefore, the Air Force would yield to the Army. But General Gaston, of the Army, replied with equal decisiveness that since the missile would be airborne, it was obviously a matter for Air Force jurisdiction.

As I explained, there was such a confusion of sounds accompanying that gentlemanly discussion that I may have missed some of the points of the remarks, but as I drew closer, an extraordinary thing happened. As the general commotion grew louder and the vibration increased, and as I came opposite the entrance, a large flying saucer whizzed past my head. Now I confess this unexpected development startled me, and since I had never seen a flying saucer before, it immediately caught my attention and I watched it sail down the corridor and land. It was then that I got the idea of personally investigating the flying saucer phenomenon, and I retreated rapidly down the hall to the point where the flying saucer had landed.

Being somewhat confused when I first approached, and it took a little time before I could begin to pick out details. As I drew closer I could see that the saucer was canted on one side, with hatches open. The little men from Mars were struggling with one of the hatches, which seemed to be jammed. I said in my best North Martian dialect, "How do you do, gentlemen." One of the little men nearest me turned and fixed me with a glare from his three eyes and simply stood there sputtering. He was laboring under some extreme tension, and for a moment I was

afraid he was going to explode. Slowly he seemed to regain his power of speech and his sputterings became intelligible. "Reliability," he said. "Why can't we have reliable equipment? How can we possibly carry out our mission, if the dammed engineers and manufacturers can't build reliable equipment?"

By now many readers are probably thinking that this paper is to be a science fiction presentation. If anyone has that idea, I can assure him that he is absolutely incorrect. This is not a science fiction presentation; science has nothing to do with it.

My conversation with the first Martian, who proved to be the leader of the group, extended into weeks, and I am privileged to give you the exclusive story of my investigation. I discovered in the course of many conversations with the leader that we can learn much from the Martian techniques, adding perspective and understanding to the methods and policies which we apply to the general problem. I would like to identify the Martian leader, but his name is unpronounceable in the English language. A literal translation of his name would be "One who penetrates for the purpose of making a hole all the way through," and a literal translation of his title would be "Important Commander." Translating this freely, it would become "Major Breakthrough." Some weeks after I met him, however, word came through that he had been promoted and he is now known as "General Breakthrough." I am greatly indebted to him for the data he has made available to me for this presentation.

My conversations with General Breakthrough were concerned with direction, organization and control aspects of research, development and production, and with governmental influence upon reliability in so far as it is conditioned by the governmental organizational pattern of control and direction. General Breakthrough, coming from an older civilization (5,000 years older, in fact), provides us with the necessary perspective needed for a look at our trends from a balanced and objective point of view. The opinions expressed by General Breakthrough are not necessarily the opinions of the author or his sponsors. That makes it legal, and besides, I have scheduled a fast flight out of town.

I learned from the General that the North Martians and the South Martians have been in a state of cold war and , therefore, in a continuous state of potential, catastrophic open warfare over the past 1,000 years. General Breakthrough likened the situation to the one now existing on the planet Earth, withssome obvious differences which I took pains to point out to him. He explained that the eruption of actual war had been forstalled on Mars by the introduction of the professor-factor.

If I interpret the General's remarks correctly, the advance of atomic science and the resulting rise of the Martians' control over their environment was accompanied by the flowering of the scientific intellectual. There arose a form of pseudo-worship of scientific intellectualism, which began with the discovery of atomic fission and mounted quickly with the engineering design of the first atomic bomb. It was assumed that all problems would yield to formulation based upon a concentration of the scientific long-hairs. In both North and South Mars, these intellectuals gradually gained ascendancy as dispensers of the final word in military weapon systems tribunals. In both areas, the frantic search for the ultimate weapon was characterized by the persistent invasion of the frontiers of scientific effort and by the constant striving for

speed, accuracy, versatility and invulnerability of weapons for the ultimate application to push-button warfare which was to insure the final answer to military superiority and national security. One year's proposed weapons were obsolete before they reached production, and the next group of weapons reached a state of obsolescence while they were still on the drawing board. From there on, the reaching ranged into the postatomic age.

While all this conversation was interesting, it was the General's conclusion which was most striking. He suggested that we had the beginnings of such a trend in the United States. In Mars the result had been most fortunate because both sides were so busy making each other's weapons systems obsolete before they could be matured and made available as usable devices in the military organizations that neither of the potential belligerents ever reached a point where they were ready for war. Since each feared the other's potential capability of the weapons in development in the laboratories, neither was in a mood for war. The general characterized the situation as the "war of the long-hairs," and he described a long-hair as a theoretical scientist with assigned engineering authority who had never been disciplined by the necessity for making equipment work in a practical mass production and application sense. I protested that there was nothing wrong with the long-hair scientist -- that the long-hair is an idea man and a very necessary specialist. The General agreed, but he qualified his agreement by saying that the long-hair scientist should stay out of the short-hair categories, since there was nothing more futile than an attempt to resolve a design into a matured manufacturable engineering product with a long-hair scientist in charge of the development.

Now General Breakthrough has suggested that we have a good start toward the perpetual challenging of the frontiers of the military engineering art and that we should encourage this approach. Suitable propaganda in Russia could encourage the perpetual search for scientific superiority and thus succeed in delaying readiness for war. The schedule for readiness would always be at least five years in the future.

"Suppose," I said, "that Russia doesn't follow our pattern of perpetual advance toward the ultimate in military equipment? Suppose Russia follows the policy of discontinuing this process of discarding something she almost has today in order to get something which is going to be a great improvement tomorrow. And suppose Russia builds a large supply of usable field operational equipment within the current art that is good enough for the job, and then challenges us while we are still frantically pushing back the horizons." The General's answer was an obvious one: "That's the risk you have to take."

"But suppose," I suggested, "we do both. Suppose we continue our challenge of the frontiers of scientific application to military weapon systems design while consolidating and constantly improving our position with an army, a navy and an air force, equipped with adequate weapons in terms of today's art." The response to this suggestion was a laugh. How could we expect to carry on one approach adequately without even considering the problem of carrying on both? It was obvious to any dispassionate observer that the frantic bidding for engineers' services, the duplication of effort, the immaturity of many engineering designs, the made-work through the switching of contracts and the random scramble of research and development contracts have created an acute shortage of engineers and scientists; and the new supply is not flowing out of the colleges

and universities fast enough to meet the rising demand needed for the broadband low-percentage yield policy of R&D. The General suggested that if we had the means for making an intelligent selection, at least half of the R&D projects, and probably more, could be thrown out without ever being missed. But, of course, the greatest problem is that of selection. When I asked the General how we would make our selection, he had no answer. He described our military weapons search, as it appears to an outsider, as a broadband evolutionary process characterized by random redundancy of effort. "It is weak in synthesis and weak in control," he said. "The control might be described as similar to the situation encountered by the three ants and the beavers," he went on to explain. "The Army, the Navy and the Air Force are the three ants which are riding a long down the rushing rapids. The log tosses from side to side, bounces off boulders and whirls into eddies and whirlpools, and each of the three ants, hanging on for dear life, is screaming, "Whee, look at me! See how I've got it under control."

"And where do the beavers come in?" I asked. "Oh," said the General, "the beavers are the busy senators and the defense department. They are busy gnawing holes in the dam to increase the water flow and create more action." "But," I protested, "despite your criticism, we've done pretty well." He looked at me quietly and said, "Have you? Your wealth of natural resources and your constantly expanding industry and population have kept you riding an economic boom, but the waste can't go on forever. The failure of the supply of natural resources, of engineers who implement the use of resources or the failure of the expansion rate of the engineering supply to keep up with the industry expansion and the rising demands of the increasing population can halt the industrial expansion, halt the creation of jobs, halt the economic boom. I say to you that the failure to pace your economic and industrial expansion with an expanding supporting supply of engineers and scientists is the greatest threat to disaster you face today. Since you cannot possibly increase the rate of training and the output of the universities and colleges rapidly enough to pace the growth pattern, I recommend that you resort to a more orderly and selective approach to engineering and scientific assignments. This would be merely a stop-gap measure and you would have to introduce a system for the careful selection and training of qualified students. I see no reason why this cannot be accomplished within your avowed social and political ideals of self-determination. There is a decided difference between control and leadership, and one marked trend in your governmental organizational structure is toward compartmentalized and fragmentary thinking supplemented by too much control and not enough leadership."

"Well," I said, "you're making some pretty wild generalizations and charges for someone so inexperienced with out institutions." The General acknowledged that this was certainly true from my point of view, but he suggested that I lacked the perspective that he brought to bear on the problem. He looked at our administrative trends from the point of view of at least 5,000 years of additional history, and he was basing his conclusions on the historical parallel patterns developed on Mars. "I'll grant your superior experience," I said, "but you're still unfair in your unsupported generalizations."

"Very well," he said, "consider this: your problem is bigness and centrali zation. I think that none of you are unaware of the frustrating complexity of your colossal military organization. It is this very massiveness of the structure which looms before you as an insurmountable barrier across the road to simple , common-sense, effective procedures for the development of suitable military equip-

ment. As I said, you are not unaware of this gargantuan body which spreads loose jointedly at times, and sometimes in unyielding formations, across the economy of your country, and even across the economy of the world. So complex is the structure, and so lacking in the complete articulation of the appendages and subappendages, that subtle control messages originating in one part of the body may never find their way through the maze to effect the nuances of performance in a particular appendage. I don't know enough about the structure to criticize it in detail, but it is important that you recognize the magnitude of the problem of bigness and understand the inherent inertia of the structure. A recognition of this problem will aid in your search for the proper articulation and control of subappendages which might hold your special interest. Bigness is a barrier to speed and flexibility.

"I note that this fact is recognized by all your large industrial organizations and that many of them have recognized the futility of piling structure upon structure in a vast system of centralized control. The frustrations, the lack of flexibility, the inability to reach decisions, the impossibility of blending policy, decision and action have caused the alert large organizations to decentralize. I recognize the fact that the decentralization of governmental structures is much more difficult. You have so many parallel lines of authority and functional setups serving multiple divisions and department heads, and cross-configurations of political interest, that simple decisions and reforms cannot be made. A general atmosphere of decision must be generated in whole areas and groups of organizations before action can be taken. This is the failing of a centralized functional plan of organization. The result is that fast action isn't possible except in special cases. Your Hoover Committee encountered this resistance to change.

"The structure is, by its very nature, self-perpetuating. Empire builds upon empire, and one empire cannot be removed unless there is universal agreement of all empires at the same level. To keep the activities of the department, the division, the groups and the individuals coordinated and identified in orderly procedures, a massive superstructure of paper work is superimposed over the whole. Tons upon tons of paper grind through the endless typewriters, hour by hour, day by day, year by year, with a rising crescendo of typewritter vibration which batters the air and is equalled only by the sharp sounds of sliding filing cabinet drawers and the shuffle and swish and crackle of papers. And with the passing of years, the production of a daily stint of typewritten pages becomes the objective as well as the pattern; and the plan and reason for relationships fade and are forgotten as the flow from forest, to typewriter, to filing cabinet, to archive, to incinerator, becomes steady, dependable and irrevocable.

"In Mars, after a few thousand years of maturing, they do these things much better. Recognizing the impossibility of altering such a structure, the North Mars engineering committee on stabilization and permanent ossification secretly installed an effective feedback loop which substantially reduces the waste without altering the general pattern of operation. It is only necessary to connect each filing cabinet to a belt system which automatically removes papers from the cabinet, depositing them in the grinding gears and moving them on to the reprocessing trough for reactivation through the automatic reclamation formulation, which feeds back reclaimed clean white paper to the stenographers' and clerks' typewriters. I recommend this for your consideration. Of course, it could be standardized on typed forms and set up with magnetic tape to keep the loop going

automatically without the stenographers and clerks, but this would be disastrous -- think of the thousands of people who would suddenly find themselves without an object in life. No, the Mars solution is far better.

"This solution accepts the immovable configuration and stabilizes the waste, and in Mars they go even beyond this. As the stabilized governmental areas of permanent redundancy became better understood, one of the brilliant independent thinkers recognized the potential of the system as a trap to vitiate the efforts of the South Martian subversives. Prior to this understanding, there had been a constant struggle to keep South Martian spies out of the North Martian governmental system. With the maturation of the redundancy formulation the policy was changed, and from then on every effort was made to identify the South Martian spies and to encourage them to enter the North Martian governmental service. They soon became so engrossed in the processing of the paper flow that their efforts at subversion were entirely vitiated. Since the adoption of this logical and realistic approach, the infiltration of subversives has ceased to be a problem." This ended General Breakthrough's harangue.

Now, of course, we do not agree with General Breakthrough at all. His criticisms are brutal and unsupported by the facts as we see them. Nevertheless, while his amplification is far too broad, if we apply a suitable attenuation correction to his remarks, we can recognize the existence of some slight residue of truth. The balance of this paper has been influenced profoundly by my discussions with General Breakthrough.

Let us now consider the problem of compartmentalizing knowledge, the subject of some very thoughtful papers in the last two years. This problem certainly influences equipment reliability. We tend to look at only a part of a problem, thus dealing in fragments of knowledge; we are becoming specialists. As the total store of information accumulates, covering all recorded human knowledge and experience, the thought that any single brain can ever encompass the whole is ridiculous. This also applies to the single category of electronic science and engineering. The rising store of valuable recorded data is mushrooming with the improvement in communication, and with the improved methods for recording and storage. The natural result has been this tendency towards compartmentalizing, segregating and specializing.

Knowledge is important only in terms of usefulness and, unless we develop new techniques for the location and selection of stored material, we shall become hopelessly involved in a recycling process, when proper selection would reveal the information already stored in the vast repository of the records of human knowledge. Work is being done to cope with this problem, and I assume that one of the first developments will be new techniques for reference and selection of library material. We may ultimately arrive at a means for recording and storing information which will be more efficient and more effective than that afforded by the use of books and periodicals. Many thoughtful people agree that the greatest problem relative to human advancement is centered around the synthesis of human knowledge. The recording and storing of knowledge is futile if we do not develop a system for locating, selecting and serving up the information when it is needed. Only through effective use of the material collected in our storage systems and in synthesizing of all knowledge relating to a particular problem, can we hope to achieve a balanced approach to the solution of problems affecting cities, countries and the world or, more specifically, weapon systems design.

While this advancement must be achieved through the development of improved methods for synthesizing the multitude of compartments of human learning, the solution must include improvement in the efficiency of personal communications among the experts specializing in the various compartments. It has been suggested by a famous engineer that we have the scientific and engineering knowledge at hand which, if applied to the problem of producing plants and animals, could banish famine and food shortage from the world. Now we know that the mere ability to produce food in quantities great enough to feed every human being on earth solves no problem in a system sense. Consider the problems of distribution, those of economic upheaval, of acceptance, taste and preferences, the problems concerning specialized technical information and the distribution of energy and chemical sources, and even the problem of taboos and religious dogma influencing any plan to ban food shortage throughout the world. And I haven't even mentioned the possible resulting increase in population and the pressures for more food, or the economic forces which would develop pressures for more wars. I merely indicate that a single compartment of knowledge will not solve the whole problem, and there must be a synthesis of all of the fundamental knowledge related to the problem if there is to be an acceptable solution. We must have a systems solution rather than a compartmentalized solution. The development of an effective means for the location, selection, utilization and synthesis of knowledge is the essential missing link in continuing human progress.

I have suggested that this problem of compartmentalizing of knowledge is keenly related to the problem of military direction and control of weapon system development. There is evidence of both saturation of usable knowledge accumulation and lack of effective synthesis and communication, with the waste compounded by the security requirements. At executive levels, this compartmentalizing approach has been recognized, but the recognition does not seem to carry with it full comprehension. The attempt at the unification of the Army, Navy and Air Force was one result of the recognition of the problem, but this very directive was itself generated under the influence of the same pattern of compartmentalized or fragmentary knowledge it sought to correct by the unification. The next attempt to synthesize the pattern of military activity was the superimposing of a vast civilian umbrella (designated as the National Defense Department) over the existing gargantuan military structure. This again was a product of frantic compartmentalized thinking. The theory seemed to be that if an organization of military experts couldn't integrate the complex elements into a pattern, then the problems could be resolved by establishing this superstructure of newcomers in the military art who reflected the industry approach and were untainted by the high impedance and inertia-without guidance system which had produced a degree of stagnation in internal military interservice coordination. This didn't solve anything because many of the most intelligent, aggressive and effective military officers now found their time wholly taken up with the problem of educating the members of the superstructure. And, of course, the educational process will never end because of the continual change of executives in the superstructure.

The assumption that the over-all solution to military coordination might lie in the application of applied industrial brainpower and methods is a wild one, because industry, in cases where large centralized organizations have developed, finds itself in precisely the same frustrating position as the total centralized military system. That we can solve the problem of military bigness and overcentralization by superimposing an overlord group of nonmilitary specialists is patently absurd. Industry itself has found it necessary to move in precisely

the opposite direction. It has found that the only answer to the problems of synthesizing knowledge in an overcentralized functional structure is to decentralize into almost autonomous substructures where there is assembled a complete team, which includes all of the necessary areas of specialization, and where the men involved can identify themselves with the problem and with the synthesis of all the information for the ultimate solution of the whole problem. If industry has found it unrewarding to move from overcentralization, to superstructure control, why should we expect such a solution to be successful in government? If we follow the governmental trend, in the next logical step we should expect the installation of a scientific council with authority to coordinate the Defense Department.

If we take a look at military arms, we find further evidence of the recognition of the need for synthesis of knowledge within the whole weapons category. The Navy, of course, has always had this understanding, since a battleship is nothing more than a floating weapons system of the most complex configuration. More recently, we have heard much about the weapons systems approach of the Air Force. I would agree that the weapon systems concept is sound, once the weapon system has been identified in terms of the whole problem of the total systems approach to national security. Unfortunately, the success of the weapon systems approach is limited by important factors. The accumulation of the original characteristics of the proposed weapons system may be based upon limited information inadequate to achieve the synthesis required for sound systems delineation. After the establishment of the system, another limiting factor is the inability to implement the concept so that the research, development and production proceed with the scientific, engineering, and dollar discipline necessary to produce practical, reliable and economically sound equipment.

One criticism is that, in our eagerness to produce the best possible device, we are constantly over-reaching our ability to consolidate, within the limits of the art, for the production of equipment which will function in the field with realistic maintenance procedures, and with tolerance and performance specifications which are realizable and practical. I believe that we neglect all too frequently to follow a process of refinement in maturing and stabilizing weapons systems, and we make obsolete one complex of unreliable devices with another advanced conglomeration that has increased potential for unreliability. Our problem is not one of the lack of intelligence of the military personnel or the civilian military laboratory experts. The general level of intelligence is precisely as high in the military as in industrial circles. The problem relates to the piling of superstructure upon superstructure. It relates to laws controlling procurement, to budget control, to political maneuvering, and to many, many details of governmental regulations and procurement procedures. Fortunately, our resources have been so great in the past that we could waste 90 per cent of our effort and material and still come out on top in terms of the performance of other countries.

We can conclude that there are serious problems confronting us. Full recognition of the situation offers a stimulating challenge. We must solve the problems of bigness, of centralization, and of compartmentalized thinking, or be faced with saturation in the application of human knowledge. Implicit in this paper is no criticism of any group, organization or individual in military, governmental or industrial circles. We have grown into this threat of stagnation together and we must find our way out together.

One obvious and basic approach which must be included in any attack upon the problems posed must begin with the education of our children. There must be renewed emphasis in the teaching of the power to learn. The whole concept of our technological civilization is demanding more and more from our brainpower. I am not at all sure that the present interpretation of the educational methods is meeting the challenge. It is universally agreed that the educational objective is the development of the power to learn. The disagreement has to do with the methods for this development.

For some, the educational process is one of stuffing information wholesale into the memory storage cells. Although this is a legitimate part of the process, education is basically the training of the brain to effectively select discipline and store materials, and ultimately to synthesize new disciplined information through forming new combinations and correlations of the existing stored material. Now, the acquiring of training for the brain may be a painless process for a very fortunate few, but for most of us, it means long, hard, concentrated effort. It means days and weeks and years of poring over books, of solving problems, of performing experiments, of reading, and more reading, of checking and cross-checking -- it means self-discipline. I know of no other way to train the brain, and since the time is so short and there is so much to learn during the training period, we should be very careful indeed about the selection of the subject matter. If our objective is to educate in the sense I have indicated -- that is, to teach the power to learn -- then we should take a look at the emphasis (or lack of it) given to basic courses in the schools of our country. I have suggested that the primary purpose of school or college training should be the development of efficient and effective procedures for selecting, integrating, correlating, synthesizing and disciplining information for brain storage and for developing the process of withdrawing the information with new combinations and new interrelationships. The storage of disciplined information is essential before effective thinking can be achieved, but the storage process is a lifelong task and it will fail miserably in the building of the supply of thinking source material if the process of selection and discipline is inadequate.

Successful training of the power to learn not only develops ability to think objectively; it leads to a maximum achievement of social adjustment and intellectual growth for all normal individuals. In education, we should constantly reaffirm our objectives to teach the power to learn, and this teaching should be implemented by the selection of the most effective training program. We should stress the fact that education is the beginning, and not the end, of learning. My own experience convinces me that subjects like mathematics, physics, chemistry, and engineering are more effective in teaching the disciplines necessary to the learning process than are the arts and humanities. If the reports I read are correct, the national trend in high school education seems to be away from these difficult subjects which require teacher discipline and student self-discipline.

Published statistics show that only about 55 per cent of high school students take mathematics, and 54 per cent take science. Such statistics make me believe that the trend is away from the teaching of the learning process. Science and engineering are essential areas of education in the technological world. I think the essence of a scientific education is the training which requires an objective evaluation of the facts in reaching conclusions. Gerald Holton, in the introduction to "Concepts and Theories of Physical Science" states, "The great moral which the progress of science teaches its students: faith in the marvelous ability of

man to arrive eventually at truth by the free and vigorous exchange of intelligence." The fundamentals of scientific procedures are antiwar.

May we digress a bit further. It should be emphasized that the development of the power to learn and the accumulation of learning is not merely a problem of materialism for the production of brainpower to dream up more gimmicks for people to use. Learning is the essence of living. It provides a comprehension of the expanding world about us -- an awareness and understanding of people, an ability to share experience and ideas. The brain is where we live. The training and enhancement of brainpower is an expansion and enhancement of living in all of its manifold and kaleidoscopic aspects. The failure to endow our children with this priceless gift -- the power to learn -- is not simply the failure to provide an earning capacity in a competitive world; it is equivalent to imprisoning them within a barrier which will forever limit the range of growth and imagination and the ability to understand and share experiences. Even more important, it limits if it doesn't wholly stultify, that satisfying experience of continuing growth of comprehension. The brain is where we live, and the power to learn is a priceless ingredient of life and living. Taken in context, it encompasses the spiritual as well as the material aspects of life. The power to learn deals with life in terms of the systems relationship to the whole environment. Now, I am not proposing that we should endeavor to be geniuses, or that we should develop generations of geniuses, but even with the level of intelligence varying widely from individual to individual, we make such little use of the total intelligence potential that effective training would enhance the wonderful living experience for everyone. The heritage of brainpower is too priceless to neglect.

In education today there is a confusion of objectives. The teachers of teachers are responsible for this. When social adjustment became the overemphasized objective, the technique of teaching became more important than the subject matter. Professor Arthur Bestor, of the University of Illinois, stated in the November 30 issue of U.S. News & World Report that we are less educated now than fifty years ago. Professor Bestor states, in part, that the schools have lost their sense of purpose. "Schools today are undertaking a large number of activities that aren't essential to education at all. The result is that these unessential activities are squeezing out the basic subjects for a large number of our students." He goes on to say that the subjects are being taught, but not as effectively as they should be. So it is not a question of omitting them entirely, but rather of treating them too casually all the way through school. At another point in his article, Professor Bestor states that the "professional educators" have become confused about the fundamental purposes of education. And by professional educators he means the teachers of teachers. The teachers themselves are just obeying orders.

We must question sharply the goals of these educators; there must be a realignment of method and substance of teaching. The scholarship level at state colleges and universities must be tightened, and especially the course prerequisites must be rigorous and adequate to force upon grammar schools and high schools the necessity for maintaining proper scholarship standards. And we must search out the intellectually competent student and see that he has a chance to take advantage of the college or university training for which he is qualified, even if he is unable to finance the training. Both the security and the financial stability of our country are dependent upon intelligent mobilization of all of our potential brainpower.

In closing, to avoid embarrassing headlines, I should explain that I really didn't encounter the flying saucer in the corridor of the Pentagon. I just made that up. Actually, I came upon the flying saucer in the Superstition Mountains near Phoenix, Arizona, and my discovery occurred about the time that the newspapers were headlining the stories about the mysterious automobile windshield chipping that rose to epidemic proportions along the West Coast. I had heard rumors as to the cause of this windshield chipping, but it wasn't until I talked with the leader of the flying saucer expedition that the rumors were confirmed.

It was entirely true that the windshield chipping was an outgrowth of component unreliability. The flying saucers reported over our country were operating far from home base, and normal maintenance procedures were impossible. The chipping of windshields was caused by falling nuts and bolts shaken from the deteriorating flying saucers.

METHOD FOR THE DETERMINATION OF RELIABILITY

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The calculation of the reliability of a device may be a complex problem. It is the purpose of this article to explain a widely applicable method of measuring reliability. Although the common experience of the authors is solely in the field of electronic and electromechanical devices, and although this article deals with such devices as models, much of the information contained herein could be applied to a completely mechanical system.

The complexity of the problem in the ordinary electronic device leads one to seek a simplification. This division of the general problem is presented here along with the definitions and mathematics necessary to arrive at a numerical expression of the reliability. The method employed has faults as well as attributes, and both will be discussed.

THE GENERAL EXPRESSION

The three factors which contribute to the reliability of a device as it leaves the manufacturer are the reliability of the design, the reliability of the component parts involved and the reliability involved in the manner in which the components and the design are fabricated. The relationship of these factors is expressed in the following equation:

$$P_a = P_d \cdot P_c \cdot P_f$$

where P_a = the over-all reliability
P_d = the design reliability
P_c = the component reliability
P_f = the reliability of fabrication.

DEFINITIONS

The reliability of the design is the probability that the required outputs will stay within the specified limits, subject only to the conditions of (a) no complete and catastrophic failure of a component part, (b) inputs staying within their specified limits, and (c) probability calculated with allowance made for the environmental conditions of use.

The reliability of the component parts is the probability that no component will fail completely and catastrophically under the environmental conditions.

The term "environmental conditions" is intended to include time, in both the design and component reliabilities.

The reliability of fabrication is defined as the probability that no significant error of fabrication (i.e., one which will cause failure) exists in the completed device after it has been inspected, tested and accepted for delivery.

With these certain conditions established and the general expression explained and the basic terms defined, the task of assigning numbers to P_c, P_d and P_f can be undertaken.

EVALUATION OF P_c, THE COMPONENT RELIABILITY

The calculation of P_c involves two separate cases. Case I involves devices in which the life of the device does not exceed the wearout period of the component with the shortest life. Case II involves devices in which the life requirement of the device exceeds the wearout period of at least one of the component parts involved.

Case I can be solved by the use of the well known product rule, $P_c = P_1 P_2 \ldots P_n$. Two major notes of caution should be interjected here. The first is the use of removal rates which are sometimes published as "failure rates." The use of these statistics will yield a pessimistic value of the reliability. The second note of caution applies to devices used in environments for which data is not available. It will be necessary to employ component engineers to determine the causes of failures so that such things as secondary failures (failures resulting from other failures) due to fabrication errors, etc., will not enter into the calculation of P_c.

Since the use of the product rule assumes a constant failure rate of the components, it loses its validity when Case II devices are considered. If one modifies the failure rates somewhat, the product rule remains a good approximation even on Case II devices. This follows because of the fact that as we replace random failures we are, in effect, randomizing the wearout period. The adjustment of failure rates would have to be a continuous process and would certainly present problems.

The manner in which we chose to handle this problem is as follows. Assume a component has a failure rate $f(t)$ (t being time), and from this calculate the distribution of the number of failures in a time that is large compared to the component wearout time. Once the distributions of the number of failures for the individual components have been calculated, these distributions can be combined statistically to yield the distribution of equipment failures. If one has a knowledge of the time required for different types of repairs, one can then compute the percentage of equipment down-time and, of course, the standard error and the confidence limits. For systems that operate for such long periods of time, this seems to be a more useful number than the simple probability of no failure in a specified time. Though, certainly the probability of no failure can be calculated.

The problem then remains to compute the failure-rate distributions. The failure rate $f(t)$ may be defined by the following conditions:

1. When $t = 0$, the component is new.

2. The probability that the component will fail between times t_1 and t_2 is

$$\int_{t_1}^{t_2} f(t)\, dt \, .$$

From this definition, it follows that $G(\tau) = 1 - \int_0^{\tau} f(t)\,dt$ is the probability of no failure in time τ. The probability of exactly one failure is

$$H(\tau) = \int_0^{\tau} f(t)\, G(\tau - t)dt \; .$$

The probability of exactly two failures is

$$\int_0^{\tau} H(t)H(\tau - t)dt \; .$$

In general then, if the probability of exactly N - 1 failures is U(t), the probability of exactly N failures is

$$\int_0^{\tau} U(t)\, H\,(\tau - t)dt \; .$$

Since the above calculations show the number of times a device must be repaired, the mean time to failure of the device may be determined. The failure-rate distribution of the individual components also yield the information necessary for the determination of spare-part requirements.

The major drawback of this method is that it requires a knowledge of the component failure rates. Although there appears to be a trend toward the gathering of such data, there does not exist today enough of this information to use the method. For the time being then, the product rule will continue to be used in the evaluation of P_c.

It should be noted here that our definition of component failure includes only that change in a component parameter which represents total destruction of that parameter. For example, in the case of a resistor, the only changes in resistance value that shall be declared a component failure are the resistor's shorting (about zero resistance), or opening (about infinite resistance). To set up any other criteria for component failure necessitates the consideration of each particular circuit application. Since component failure rates must already be adjusted to varying environments, a further separation by circuit application would present an almost staggering data collection and reduction task. The ability of a circuit to withstand changes in component parameters we shall discuss in the next section.

EVALUATION OF P_d, THE DESIGN RELIABILITY

To the authors' knowledge, there exists no general method for finding P_d. There is however a method that applies to all linear circuits and to a large class of nonlinear circuitry. In addition there are several other techniques which may be used. The basic precept of the method we advocate is the criteria of the separable function.

Let the output of a circuit be given by $F(x_1, x_2, \ldots, x_n)$ where the x_i are the independent variables whose distributions are known. The function F will be called separable if it is possible to evaluate F by evaluating functions each of

which is of two variables only. For example, if $F = x_1 + x_2 + \ldots x_n$, let $y_1 = x_1 + x_2$, $y_2 = y_1 + x_3$, $y_i = y_{i-1} + x_{i+1}$, then $y_{n-1} = y_{n-2} + x_n = F$. The output of any linear network can be shown to be a separable function of the input and the component parameters involved.

If the output of a network is described by a separable function, then it is possible to evaluate the distribution of the output from the distributions of the variables. To establish this, it is only necessary to show that the distribution of a function $g(x_1, x_2)$ of two variables can be found. Divide the interval (0,1) into $m + 1$ equally spaced intervals (the size of m depending on the accuracy desired). Find the values of the cumulative distributions of x_1 and x_2 at each of the ordinates equal to the m points of the division found above. Call these values $x_{11}, x_{12}, \ldots x_{1m}, x_{21}, x_{22}, \ldots x_{2m}$, and then calculate the m^2 values $g(x_{1i}, x_{2j})$. From these values one can form another cumulative curve and select a new set of m values for further pairing. If m is selected as less than 50, this process becomes inaccurate after several pairings. A selection of m in the order of 100 seems a reasonable compromise between accuracy and the number of computations required. The number of computations could be expressed as $(n - 1)\, m^2$ where m is as defined above and n is the number of distributions involved. The error of a single pairing should not exceed 1 per cent when $m = 100$, and the degree of such error is approximately proportional to $m^{-\frac{1}{2}}$.

An alternate method can be used if the density functions of x_1 and x_2 are known. Let $y = g(x_1, x_2)$, $x_1 = h(y, x_2)$, $f_1(x_1)$ be the density function of x_1 and $f_2(x_2)$ be the density function of x_2 then the density function $f_3(y)$ is given by

$$f_3(y) = \int_{-\infty}^{\infty} f_1\left[h(y, x_2)\right] f_2(x_2) \left|\frac{\partial h(y_1 x_2)}{\partial y}\right| d\, x_2 \,.$$

If the function $F\,(x_1, x_2, \ldots, x_n)$ is not separable, a generalization of the above equation may be used. If, however, the variables $x_1, x_2, \ldots, x_n$ are not independent, the above methods cannot be applied. It may be possible to evaluate the integral

$$H(y) = \underset{F<y}{\iint\cdots\int} g(x_1, x_2, \ldots x_n)\, dx_1, dx_2 \ldots dx_n$$

of the joint probability distribution function $g\,(x_1, x_2, \ldots x_n)$ and thus find the cumulative distribution function $H(y)$ of the output.

While direct evaluation of the integrals may be impossible, Monte Carlo methods can be applied. Assume the function g is effectively zero everywhere except in a finite region R of the $x_1, x_2, \ldots, x_n$ space (R existing for all distributions which are continuous almost everywhere). Let $P_1, P_2, \ldots, P_n$ be a set of random points in the region R, and let $g(P_1), g(P_2), \ldots, g(P_n)$ be their associated probabilities. Then the probability that $F < y$ is given by

$$\lim_{n \to \infty} \sum_{F<y} g(P) \Big/ \sum_{1}^{n} g(P) \,.$$

If

$$I = \sum_{F < y} g(P) \text{ and } A = \sum_{1}^{n} g(P)$$

then the standard deviation of the estimated probability is approximately*

$$\left(\frac{1 - I/A}{n - I/A}\right) 1/2$$

It is sometimes possible to evaluate functions of several random variables by transforming the expression to a sum of known independent distributions. It can be shown that if x has the distribution f(x) and if g(x) is any continuous, invertable function such that g'(x) exists then the distribution function of g(x) is $f(x)/\left|g'(x)\right|$†.

EVALUATION OF P_f, THE FABRICATION RELIABILITY

It is recognized that the importance of this factor will diminish rapidly as the device is operated; indeed P_f should be unity after some use. The rapidity with which it will approach unity is a function of the usage environment, the skill of the maintenance personnel, and the operators' ability to recognize improper operation. There are other factors as well, but we will limit our discussion to the probability that the device has been properly assembled as it leaves our custody. We shall also discuss what to do if our fabrication reliability is too low.

In order to simplify the gathering of data, fabrication will be divided into elementary processes. An elementary process shall be defined as one which must be entirely repeated or reworked in order to correct an error. Further, an elementary process must be completed by a single operator. Examples might include placing a tube in a socket or attaching a wire to a terminal.

If we define P_i as the probability that an elementary process has been correctly completed on a device being shipped, we can then define P_f as either $P_f = P_1 \cdot P_2 \cdots P_n$ where the various P_i represent the probabilities of discrete elementary processes, or more simply as $P_f = P_i^n$ where n is the number of elementary processes involved, and P_i is the geometric mean of $P_1 \cdot P_2 \cdots P_n$. On a low rate line the simpler expression is more useful.

The probability that as a process is done it is done correctly, is defined as the accuracy of assembly. This number is purely a measure of the assembly efficiency and is independent of the inspection. The probability that if a process is done incorrectly the error will be detected, is defined as the accuracy of inspection. In this paper the word "inspection" is used to denote the entire test and inspection procedure used in the manufacturing process to detect an error.

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*"The Nature of the Monte Carlo Method," Julian Keilson.

†"Mathematical Statistics," Wilks.

Assume that a process is done with an accuracy of assembly A_i and inspected with an accuracy of inspection B_i. Further, if the inspection detects an incorrect process, assume that the process is repeated and reinspected, then:

$$P_i = \frac{A_i}{1 - B_i + A_iB_i} \; .$$

This expression is derived as follows. Let $Q_1 = 1-P_i$ be the probability that an incorrectly completed process passes inspection. If it is only inspected once this probability is $(1-A_i)\;(1-B_i)$. If it is inspected twice, the probability is $(1-A_i)B_i(1-A_i)(1-B_i)$ or $(1-A_i)^2B_i(1-B_i)$. The probability that the process is incorrectly completed n times, rejected n-1 times and accepted the nth time is $(1-A_i)^nB_i{}^{n-1}(1-B_i)$. Thus,

$$\begin{aligned} Q_i &= (1-A_i)(1-B_i) + (1-A_i)^2B_i(1-B_i) + (1-A_i)^3B_i{}^2(1-B_i) + \cdots\cdots \\ &= (1-B_i)(1-A_i)\left[1+B_i(1-A_i) + B_i^2(1-A_i)^2 + \cdots\cdots\right. \\ &= \frac{(1-B_i)(1-A_i)}{1-B_i(1-A_i)} \\ &= \frac{1+A_iB_i - A_i - B_i}{1 - B_i + A_i\,B_i} \end{aligned}$$

or

$$P_i = \frac{A_i}{1 - B_i + A_i\,B_i} \; .$$

If a process is inspected more than once even though it passes the first inspection, the above equation can be altered to allow for this. It is clear that A_i and B_i must be evaluated if P_f is to be found.

One can obtain B_i to any desired accuracy by inspecting an assembly several times and observing the accuracy of the first inspection by assuming the succeeding inspections are perfect. A_i can be determined in the same manner and to the same order of accuracy. Information to compute A_i and B_i is usually readily available in the form of results of quality audits, feedback from prime contractors or field reports.

A high-rate production line producing a fairly simple assembly and utilizing a continuous quality audit on a sample basis was selected to use as a model. The information available included n, the number of elementary processes involved; d, the number of defects found in the line process; and P_f, the percent defective units found in the quality audit. The geometric mean, P_i, was obtained directly by dividing the logarithm of P_f by the number of elementary processes per unit and taking the antilog. A_i was determined by dividing the total defects (line defects plus percent the quality audit indicated being missed) by the total number of elementary processes involved. From these two then, B_i was found. This procedure obtained the following results: $P_i = .999924$, $A_i = .999697$ and $B_i = .74923$.

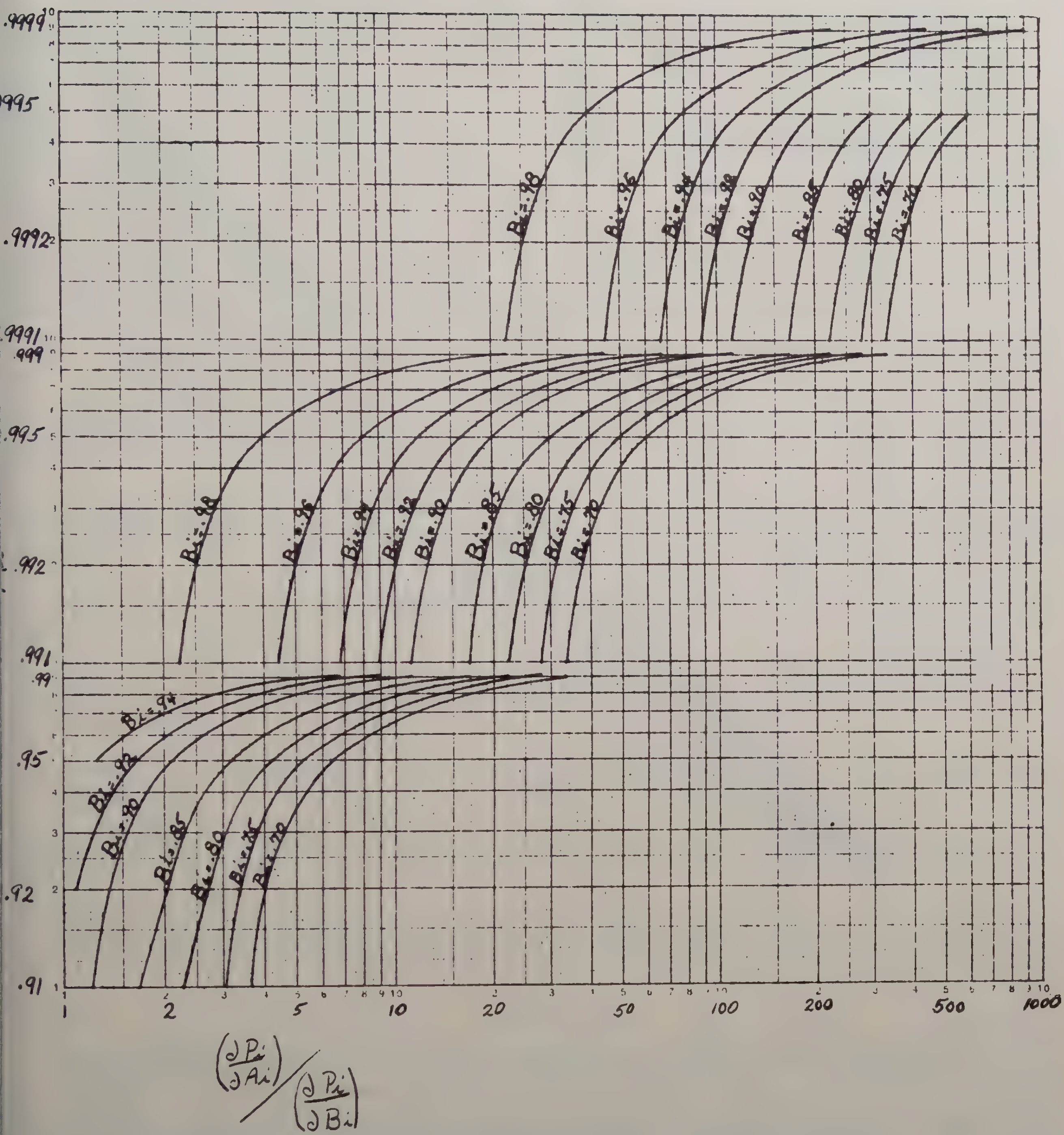

Fig. 1

The assumption was then made that of the units found defective in the uality audit, there was only one error per defective unit. Since there were nly about 1/9 as many total defects as units this assumption was thought to be alid enough. Computing B_i then by dividing the number of defects found in the ine process by the sum of the line defects and the assumed number from the uality audit, the result was $B_i = .75432$. The results being of the same order, o further computations were thought necessary.

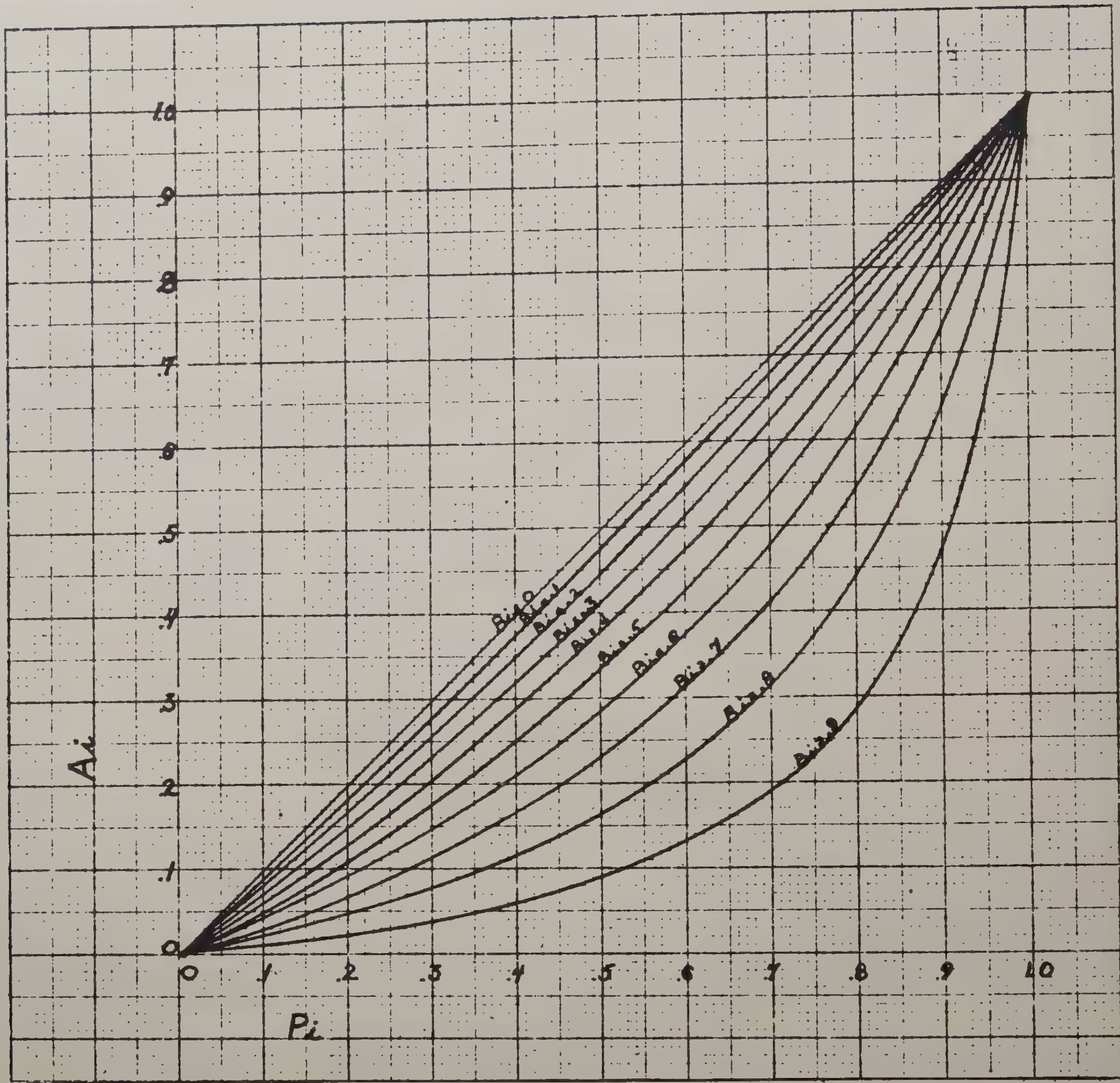

Fig. 2

An assembly of considerably greater complexity was then examined and as could be expected, A_i was of the same order and B_i was considerably higher, yielding a P_f of the same order of magnitude as the simpler device. Using the procedures already outlined, if defects were classified as to their effect upon equipment performance, P_f could be determined as a true part of equipment reliability.

If the value of P_f obtained is not high enough, one can analyze the assembly and inspection to determine the most effective way to improve reliability. To aid in this, from the basic formula we have

$$\frac{\partial P_i / \partial A_i}{\partial P_i / \partial B_i} = \frac{1 - B_i}{A_i(1 - A_i)} .$$

This expression is a measure of the relative importance of assembly and inspection and is presented graphically in Fig. 1. With a little experience one can very quickly determine what inspection is doing for the product. Experience demonstrates that the number should vary from about 20 for a complex device to in the order of 1,000 for a simple device. If the number would be much above 1,000, inspection would be contributing so little that it could be abandoned with little effect on P_f. Figure 2 is a graphical expression of the basic formula involving A_i, B_i, and P_i.

In conclusion it should be stated that slight modifications of some of the techniques discussed would result in a method for accurately predicting the expected reliability of a device in the preliminary design stage.

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